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Training Efficiently in Virtual Environments: Determinants of Distance Perception of Stationary Observers Viewing Stationary Objects

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14. ABSTRACT *(Maximum 200 words)*:

The accurate perception and estimation of distance is an important element of many military tasks. It is necessary for orienting oneself on the battlefield, for making optimal use of terrain features during navigation, and for judging the distance from one point to another. It is also a component of both route and configuration knowledge and acquisition. In order to maximize transfer from Virtual Environment (VE) to the real world, it is important to develop an understanding of the capabilities and limitations of this new training medium. Toward that end, the present study sought to gain insight about the conditions affecting distance estimation of VEs. The purpose of this research is to examine factors that influence the perception of distance in VEs. Two experiments were designed to investigate the relative effects of such factors on distance estimates of a stationary observer positioned at near and medium distances from an object. Factors found to improve distance estimates in these experiments will be incorporated into the design of VEs for subsequent investigations.

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FOREWORD

Distributed Interactive Simulation (DIS) technology can be applied to meeting training, mission, rehearsal, concept development, and test and evaluation requirements within the U.S. Army. Recently, the Army has been investing in the further development and application of these technologies. Their capabilities for representing aviation and mechanized weapon systems within a DIS battlefield have been demonstrated. On the other hand, the Virtual Environment (VE) technologies needed to involve dismounted combatants are immature, and a satisfactory capability does not yet exist. There are numerous behavioral and training effectiveness issues that must be considered as VE technology is applied to representing dismounted combatants. The U.S. Army Research Institute for the Behavioral and Social Sciences (ARI) has been conducting both basic and applied research to address these issues. The University of Central Florida's Institute for Simulation and Training is providing computer and engineering support to our efforts.

This report describes basic research in distance estimation, which is a key component of many military tasks. It explores factors that may enhance or degrade the ability of soldiers to accurately estimate distances in VEs. The research employs simple VEs to determine the effects of potentially important factors, including resolution and display field of view.

The ARI Simulator Systems Research Unit conducts research to improve the effectiveness of training simulators and simulations. The work described was conducted under the Independent Laboratory In-House Research (ILIR) program.

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TRAINING EFFICIENTLY IN VIRTUAL ENVIRONMENTS: DETERMINANTS OF DISTANCE PERCEPTION OF STATIONARY OBSERVERS VIEWING STATIONARY OBJECTS

EXECUTIVE SUMMARY

Research Requirement:

The Army is increasing its use of Virtual Environment (VE) technology for training and mission rehearsal. Of particular interest is the development of a suite of VE technologies appropriate for training dismounted soldiers. Current VE systems provide a sensory experience which clearly differs from the real world. The visual fidelity of helmet mounted displays (HMDs) is degraded in a number of ways. Both the level of visible detail and the field of view (FOV) are typically reduced. In addition, these displays have a fixed focal length that eliminates the ability of an observer to use accommodation as a distance cue. This reduction in visual fidelity can lead to distortion of distance perception in VEs.

The accurate perception and estimation of distance is an important element of many military tasks. It is necessary for orienting oneself on the battlefield, for making optimal use of terrain features during navigation, and for judging the distance from one position to another. It is also a component of both route and configuration knowledge acquisition. In order to maximize transfer from VE to the real world, it is important to develop an understanding of the capabilities and limitations of this new training medium. Toward that end, the present study sought to gain insight about the conditions affecting distance estimation in VEs.

The purpose of this research is to examine factors that influence the perception of distance in VEs. Two experiments were designed to investigate the relative effects of such factors on distance estimates of a stationary observer positioned at near and medium distances from an object. Factors found to improve distance estimates in these experiments will be incorporated into the design of VEs for subsequent investigations.

Procedure:

Distance judgments were made by subjects viewing simple VEs through a monochrome, stereoscopic, binocular display. Subjects in the first experiment (N=24) used a magnitude estimation procedure to generate distance estimates to an object placed along a corridor at distances of 10 to 110 feet. Independent variables included object size (2 levels), type of floor pattern (2 levels), scale of the floor pattern or texture (3 levels), and distance (6 levels). Subjects also used a magnitude estimation

procedure to generate distance estimates to a real-world object placed along a corridor at distances of 10 to 110 feet. Dependent variables included estimated distance, response latency, and relative error. Subjects in the second experiment (N=28) used a magnitude estimation procedure to generate distance estimates to a wall at the end of a corridor 1 to 12 feet away. Independent variables included type of wall pattern (2 levels), texture of wall pattern (2 levels), field of view (2 levels), and distance (12 levels). Dependent variables included distance estimation, response latency, and relative error.

Findings:

Subjects in the first experiment consistently underestimated distances in both VE and in the real world. Distance estimates were more accurate in the real world than in VE. Distance estimates were significantly affected by both object size and floor texture, but not by the floor pattern type. Object size influenced distance estimates to a greater degree than did texture. Texture, pattern type and object size interacted with each other and with distance in a complex manner to affect the relative errors made in estimating distances. The most accurate estimates occurred when the fine-textured, bone-shaped floor pattern and the smaller object were used.

Subjects in the second experiment consistently underestimated distances judged using a wide field of view and overestimated distances judged with a narrow field of view. Distance estimates were significantly affected by both field of view and wall pattern. Significant interactions of distance with field of view, texture, and pattern revealed that these variables had greater effects at the closer distances. The most accurate estimates occurred with a wide FOV and a rich, finely textured pattern. When no texture was used on the wall, distance discrimination was very poor at distances of less than 5 feet.

Utilization of Findings:

VEs are very likely to be used in training dismounted soldiers in the near future. For this training to be effective we must identify potential problems with this technology and overcome them. This research suggests that better utilization of current VE technology coupled with improvements in this technology will lead to increases in the effectiveness of VE as a training medium. For example, the judicious application of finely textured patterns to walls and other objects may improve the accuracy of distance estimates in VEs. It also suggests that wide FOV displays result in better distance estimates and should be used in tasks where accurate distance judgements are critical.

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Introduction

The Army is increasing its use of Virtual Environment (VE) technology for training purposes such as mission planning and mission rehearsal. In order for this training to be effective and efficient, it is important to develop an understanding of this new training medium. How does training in a VE differ from training in the real world and how can we manage any differences to optimize positive transfer from VE to the real world?

The current state of VEs is such that they clearly provide an experience that differs from the real world. The visual fidelity of head mounted displays (HMDs) and other VE displays is usually degraded in a number of ways. The level of visible detail of objects is typically reduced. The perspective of a scene might be distorted. Also, the displays typically have a fixed focal length which prevent a trainee from fully using some perceptual cues such as accommodation and convergence (Rinalducci, 1994). Such differences between VE and real world have the potential to reduce the transfer of VE based training to the real world. Recognizing this, it becomes important to understand the extent to which the perceptual factors important for performing core military tasks are altered in the VE and how we might mitigate any resulting negative effects.

Distance Estimation

Jacobs, et al., (1994) have identified numerous tasks that are critical to individual combatants (i.e., dismounted infantrymen) and are candidates for training in VE. A sub-component of some of these tasks is the accurate perception and estimation of absolute distance. It is critical for numerous tasks at a range of distances. For example, it is critical for tasks such as determining one's position in the environment, avoiding collisions while moving through the environment, and judging the distance between covered and concealed positions.

The study of distance perception per se is not new. Researchers have previously studied distance estimation in both naturalistic and laboratory settings (Gibson and Bergman, 1954)(Galantner and Galantner, 1970). A common finding is that people are less than accurate at estimating distances, even to familiar objects. Wright (1995), using data from several studies, reports that typical real-world distance perceptions are often 87-91 percent of actual distances. Distance estimation research has identified an array of cues that, depending on conditions, can affect the perception of distance. We will now discuss various types of distance cues that are relevant to the perception of distance.

Distance and Depth Cues

When discussing distance and depth cues, it is helpful organize them into a taxonomy. Most distance and depth cues can be thought of as falling into one of the following groups (Kaufman, 1974); physiological cues, kinetic or motion cues, and static or pictorial cues. For distance perception in VEs, it is also necessary to consider system induced cues.

Physiological cues refer to those cues associated with the visual system of the observer. These include the cues of accommodation, convergence, binocular disparity, and stereopsis. *Accommodation* refers to changes in the thickness of the lens of the eye necessary to clearly focus the images of object at different distances. Changes in the muscles controlling the thickness of the lens are detected by the nervous system and provide some information regarding the depth of objects. *Convergence (and divergence)* refer to the turning inward and outward of the two eyes necessary to maintain the image of an object on corresponding areas of the two retinas. *Binocular disparity* refers to differences in the images of the same object at the two eyes. The source of this disparity resides in the fact the two eyes are spaced apart. The amount of disparity varies as a function of distance, with closer objects resulting in greater disparity. Many stereoscopic displays seek to emulate binocular disparity by presenting slightly different images to the two eyes with some overlapping of the images. The term stereopsis is often used (somewhat incorrectly) to refer to binocular disparity. *Stereopsis* actually refers to the collective effects of viewing the world with two eyes. Binocular disparity is one such effect.

In general, the current state of VEs and other imaging displays, does a poor job of providing good physiological depth cues (Rinalducci, 1994). One of the main features of VE technology that distinguishes it from standard imaging displays such as computer monitors, is display stereopsis. *Display stereopsis* refers to the technique of displaying slightly different images to each eye which show a virtual scene from slightly different angles. The intent is to reproduce the effect of binocular disparity that is present in the real world as a short range depth cue. Indeed, this technique often does induce a sense of stereoscopic depth in the scene (Wickens 1990). However, there might be problems associated with the use of this technique in stereoscopic displays. Rushton and Wann (1993) suggest that in practice, such displays cause a conflict between the other physiological cues of accommodation and convergence. This conflict stems from the requirement to accommodate to a fixed distance in order to see the images clearly. As one views objects that appear to be at different distances, as indicated by changes in binocular disparity, the eyes naturally converge and diverge. These vergence eye movements are cross-coupled with accommodation, such that, changes in one results in changes in the other. The result is a conflict where convergence must be resisted in order to maintain a fixed level of accommodation. This is likely to lead to eye fatigue as the viewer strains to keep their eyes from converging.

Kinetic or motion cues refer to those cues which result from the movement of the observer, the object being observed, or both. Motion of either the observer or object being observed is a necessary but not sufficient component of kinetic cues (DeLucia, 1991). Examples of such cues include motion parallax, motion perspective, and the kinetic depth effect. *Motion parallax* refers to the observation that as objects move laterally across one's field of view, closer objects appear to move at a greater velocity than do farther objects. This concept was refined by Gibson (1979) to describe the relationship among elements in an array (i.e., texture elements). Indeed, Gibson would claim that an array of elements is necessary to provide a gradient of motion parallax which conveys a perception of depth. This concept is referred to as *motion perspective*. In contrast, the velocity difference between two individual elements would be insufficient to convey a perception of depth. This is not necessarily contradictory to the notion of motion parallax, since in practice, real objects are composed of arrays of elements rather than single elements. Changes in the total optic array (i.e., all the elements of all visible objects) provide spatial information regarding our position relative to other objects, as well as the speed and direction of movement of ourselves or other objects. For example, the array of elements comprising an object will appear to expand and contract as the distance from us decreases (expand) and increases (contract). The rate of expansion varies as a function of distance in a manner similar to motion parallax. Closer objects appear to expand at a greater rate than farther objects. This accelerated expansion of near objects is responsible for the so called "looming" effect. That is, rapid angular expansion of an object in all directions cues us that we are on a collision course with that object. Lee (1976) has shown that the rate of this expansion provides information which allows drivers to estimate when they will collide with another car.

The *kinetic depth effect* refers to the observation that as a three dimensional object moves (i.e., tilts or rotates) the image that object casts on an observer's retina undergoes systematic changes. If this image changes in both length and direction, a perception of depth results. Motion and the products of motion are considered to be important depth cues. It is a dominant cue which can act to either enhance or diminish the salience of other depth cues, but the salience of motion itself is not diminished by other cues (Wickens 1990). Motion has been shown to dominate most other cues including stereopsis, another strong depth cue. Thus, Wickens, Todd, and Seidler (1989) suggest the need for caution in generalizing from static displays to dynamic displays.

Current VE's do provide fairly realistic motion cues. An observer's view of the environment changes as the result of head and body movement. The geometry of the environmental models typically provide for naturalistic motion parallax and motion perspective cues. There are some potential limitations, however. Since motion perspective is dependent on some minimum amount scene complexity as provided by object density and/or inclusion of texture, the reduced resolution of many VE displays could limit the value of this cue. Additionally, the system lags seen in some low end systems could be detrimental in a couple of ways. First, if the rendering and presentation of the scene is not smooth and continuous as the observer moves through the environment, the scene will appear to pause, then jump ahead. This is most likely to occur when the observer is moving or quickly through the environment or rapidly changing their direction of gaze. Such inconsistencies in the visual display, could diminish the value of all the motion related cues. Second, such visual aberrations can be disturbing to the observer and can contribute to the development of simulator sickness (Kolasinski, 1995; Pausch, Crea and Conway, 1992).

Pictorial or static cues are those cues that are inherent in the visual scene and require no motion of the observer or object to convey a sense of depth. They are among the most familiar distance cues being a common part of most art and psychology curriculums. Examples of pictorial cues include: linear perspective, detail perspective, interposition or occlusion, relative brightness, relative size, height in a plane, and shadows and shading. *Linear perspective* refers to the apparent convergence of corresponding points toward a vanishing point as a function of distance. It is most often demonstrated by the converging of parallel lines seen in railroad tracks or a road. Related to linear perspective, *detail perspective* is the apparent convergence of all elements in a surface texture or pattern as distance from the observer increases. *Interposition* refers to the very powerful cue which results when one object partly covers or obscures another object. An observer will nearly always see the partly covered object as behind the closer object. *Relative brightness* also serves as a distance cue. We tend to see brighter objects as being closer than dimmer objects. *Relative size* is probably one of the most familiar pictorial distance cues and is particularly salient for object of familiar size. Generally, as the distance to any object increases, its apparent size decreases. This is sufficient for judging the relative distances of similar objects, even is the objects are unfamiliar. However, if the objects are familiar to us, the change in apparent size is much more useful for judging absolute distance. *Height in a plane* refers to the observation that as the distance to an object increases, it appears closer to the horizon and higher in the vertical plane than an object that is closer. *Shadows and shading* can also affect the perception of distance. While their value as a reliable distance cue is debatable, their presence in a viewed scene makes the scene appear more natural and may help reinforce other cues. Presumably, we are accustomed to objects being illuminated from above. Thus, we expect shadows cast by objects to be in a downward direction. Also, the shape and luminance of shadow areas provide some information about the position of objects relative to the light source.

Current VE's do a good job of presenting most pictorial cues. Many of these cues are inherent in the rendered scenes and require no additional provisions. There are, however, a few ways in which pictorial cues might be limited or distorted in VEs. The primary limiting factor is the reduced resolution of many HMDs and other VE displays. This reduced resolution could cause the fine details of detail perspective to "drop out" prematurely. This happens when the size of the detail to be displayed is smaller than the pixels of the display. The effect is that the individual texture elements get smaller and smaller as distance increases until, at some point, they abruptly disappear or merge. As a result, the depth of the textured area might appear to be shortened or compressed. A second way in which pictorial cues could be distorted results from the limited FOV available in most VEs. A limited FOV eliminates cues in the periphery, thus increasing the importance of centrally located cues. This might result in a rather unnatural situation where typically weak or secondary distance cues become the most salient cues available. In some cases, these centrally located cues might be inadequate to allow accurate distance perception or might be absent altogether. An example of this problem is the situation where an observer is approaching a turn in a hallway and must judge when to initiate rotation of their virtual body. As the observer nears the turn, the wall before them appears to expand until it fills all of their limited FOV. Perspective cues pass into the periphery and are lost, leaving only the flat surface of the wall visible. If the wall surface has a texture on it, this becomes the most prominent cue. If the wall surface has no texture, it will be very difficult for the observer to judge their distance from the wall. Another possible source of distortion for pictorial cues is unrealistic lighting effects. In many VEs there is no external light source defined, such as the sun, and the luminance of objects can be controlled independently. In practice, this can result in all the objects in a scene having nearly equal luminance. Thus, some objects appear brighter than they would if illuminated only by an external source, as if the light source is within the object. Other objects might appear dimmer than they would in the real world (i.e., with external illumination). The unrealistic brightness/dimness of these objects might confuse the observer, thus making relative brightness an unreliable cue for depth. Unrealistic lighting effects, can also degrade the value of shadows and shading as depth cues by distorting or eliminating them.

System induced cues refer to any effect on perception that results from stimuli being processed by or displayed on an imaging system. These cues are often not really cues at all, but rather miscues. That is, alterations of natural cues by an imaging system often result in perceptual distortions of the displayed environment. We have touched on some of these in our discussion of the other types of depth cues. Examples of system induced cues include reduced horizontal and vertical fields of view, incongruence of computed and displayed FOVs, and reduced display resolution. The *horizontal and vertical fields of view* that are provided by imaging displays are almost always less than one's natural field of view of approximately 120 degrees vertical by 180 degrees horizontal. This reduced FOV might affect the observer's monitoring of the environment. As a result, observers might engage in excessive head movement in order to see all that they could normally see without head movement. Such increased or exaggerated head movement might lead to the development of simulator sickness (Regan, 1993; Kolasinski, 1995). Conversely, observers might not move their heads very much. They might exhibit a level of head movement that is appropriate for the real world. This basal level of head movement in conjunction with a reduced FOV would result in an observer attending to less of the environment than they would in the real-world. Heavy or bulky head mounted display may further discourage head movements in VEs, thus exacerbating the problems resulting from a reduced FOV. Another system induced cue is *incongruence of computed and displayed FOVs*. Such incongruence might result in distortions of distance perception (Psotka, Davison and Lewis 1993). While combining different levels of computed geometric FOV and display FOV, Psotka et al.(1993) observed displacement of the perceived egocenter or eye station point of the observer. While distance perception per se was not directly measured in their study, it is reasonable to conclude that such perceived displacement of the eye station point would result in distortions of perceived distance. Psotka et al. (1993) discuss their findings as resulting from the observer's treatment of the available FOV as if it were a full 180 degrees. To the extent that the computed or geometric FOV is less than 180 degrees, the observer's perceived egocenter is expected to be displaced. As discussed above, *reduced display resolution* can have a limiting effect on depth cues including motion perspective and detail perspective. Reduced display resolution can also degrade the general appearance of a VE. Many VEs have a cartoon like appearance which results from a lack of fine details such as texture. In some cases, the resolution of the display will not support much fine detail, in other cases the detail is simply left out. This scarcity of visible detail might reduce the overall realism of one's experience and might decrease the amount or degree of presence felt by the observer (Witmer and Singer, 1994).

Distance Perception in VEs and Other Simulations

Recently, researchers have begun to study distance perception in VEs and other imaging systems with somewhat mixed results. Roscoe (1984) reports that a number of studies show a systematic overestimation of distance when a 3D space is viewed with imaging systems ranging from periscopes, to CRT displays, to night vision goggles. He found that magnifying objects from 1.20

to 1.29 times their original size will cause those objects to appear at their correct distances. He attributes these findings to the distortion of both stereopsis and accommodation cues, which are not fully supported in most current VE displays. Other researchers have found a pattern of underestimation of distances in VEs. In a study investigating the effects of ground object detail and density, DeMaio, Rinalducci, Brooks, and Brunderman (1983) report altitude perceptions of approximately 80 percent of actual for the best performing (i.e., highest object density) conditions. Wright (1995) used a magnitude production technique with Army helicopter pilots and found large underestimates of various distances; 41 percent of actual for forward, 50 percent of actual for lateral, and 72 percent of actual for altitude estimation. These large underestimates were observed despite the use of a wide FOV (i.e., 65 deg. vert. x 125 deg. horz.), and a high resolution(i.e., 1.5 arc min per TV line for the inset) helmet mounted display. These findings suggest that improved image quality alone might not result in more accurate distance estimations. Lampton, Singer, McDonald, and Bliss (1995) also found a tendency to underestimate distances in VE, and the amount of underestimation in VE was much worse than in the real world.

While real world and laboratory researchers have identified numerous perceptual factors (i.e., pictorial, kinetic, physiological cues) that can affect the perception of distance and researchers working in simulation have identified additional hardware and software factors (i.e., system cues) that might influence the perception of distance in such environments, the extent and nature of these effects is unclear. Factors that exert a strong, clear effect in the laboratory or real world might behave quite differently in a VE. Moreover, the ways in which these various factors might interact are very difficult to predict as some are likely to be additive or redundant while others might conflict with one another. Additionally, the relative effects of such factors might vary as a function of the task being performed. The systematic investigation of those factors necessary for accurate perception of distance and self motion is an important area of research (Padmos and Milders, 1992).

Task Characteristics

Recognizing that the factors important for accurate distance estimation are often task dependent (Wickens,1990), we began by examining fundamental tasks of which distance perception is a sub-component. One such task is the perception of absolute distance from a stationary observer to a static target at medium ranges (distances of 10 to 110 feet). We will refer to this task as the *distant viewing task*. The accurate perception of such distances is important for determining one's position in a VE relative to other objects (e.g., when moving between covered positions in the field or in built-up areas). A second task of interest is the estimation of absolute distance from a stationary observer to a near object or surface (distances of 1 to 12 feet). We will refer to this task as the *proximate viewing task*. Accurate distance perception at such near distances is necessary for avoiding collisions while moving in a VE and in judging when an object is close enough to reach or grasp. It was observed previously that people often collided with door ways and walls while moving through VEs (Witmer, Bailey, Knerr, 1994). We will now discuss each task separately.

Distant Task

This task requires a stationary observer to view a static target at medium to far ranges (e.g., 10 to 110 feet) and estimate the distance from themselves to the target. In this task, the observer normally would have some kinetic cues available (e.g., slight motion parallax resulting from head movements). This, however, would likely exert only a weak influence at the distances in question. Kinetic cues represent an entire class of depth cues that will be examined in later experiment(s). Thus, in the current experiment(s), possible kinetic cues were controlled by restricting head and body movement.

The cues of primary relevance to the distant task are static or pictorial cues. To a lesser extent, system induced cues and physiological cues might also affect this task. Some cues were inherent in the VE and were not systematically varied. For example height in the plane, and linear perspective would vary as a function of distance but should be redundant to each other and consistent across all conditions. Stereopsis was provided in the scenes and it undoubtedly varied as a function of distance, but was not expected to have much affect at distances beyond 30 feet or so.

The role of texture. The main cues of interest in the current study are variations of what is often referred to as detail perspective, gradient of texture density, or simply as *texture*. The basic idea is that the relationship among the elements of a texture varies as a function of distance. This is true of all textured surfaces regardless of the their orientation relative to the observer.

Research on the performance effects of texture in computer generated scenes is limited. Most of the work that has been done in this area concerns the utility of texture for simulated low-level or nap of earth flight (Kleiss and Hubbard, 1993; DeMaio et al 1983). Generally, these studies find that greater scene detail and object density result in more accurate estimation of altitude and improved detection of altitude change (Rinalducci et al 1983, Kleiss and Hubbard, 1993. As a result, a common attitude regarding use of texture is to put in as much as the budget allows because more is better. While this is often the case, it might not be true in all cases. An experiment by

Garness, Flach, and Stanard, (1994) reports that the type of texture interacts with the rate of movement to affect performance in an altitude control task. They suggest that for high rates of movement, the extraneous "information" provided by some types of textures simply acts as noise in the signal and actually makes it more difficult to discern changes in altitude.

Extrapolating from such flight studies, Rinalducci (1994) points out that some minimum density of textural elements is required to support the perception of optical flow consistent with movement. He also indicates that the minimum density will vary with the task characteristics, for example, distance of the eye point from the textured surface and rate of movement (if any).

With Regard to VE's specifically, research on the role of texture is rather limited. Many VE's employ little texture resulting in environments and objects with a cartoon like appearance. One notable exception is the highly textured environment employed by Witmer et al. (1994). A few studies have been conducted that are directly relevant to the utility of including texture in VE's. Surdick et al. (1994) examined the effectiveness of texture and several other depth cues in a VE. Three perspective cues (i.e., linear perspective, foreshortening, and texture) were among the most effective. It is interesting to note that texture incorporates the properties of both linear perspective and foreshortening. In a study comparing distance estimation in the real world and a VE, Hale and Dittmar (1994) suggest that the absence of surface texture on some of their stimuli resulted in reduced accuracy of distance judgements.

Based on the limited work in the area, we might conclude that texture can serve as a effective depth cue. Further, we might conclude that texture can result in systematic differences in distance perception. However, there are a number of unanswered questions regarding the value of texture in VE's. For example, could texture be used to compensate for some of the systematic distortions of distance observed in VE's (Wright, 1995) thus resulting in more accurate distance estimations. If so, are some textures more effective than others in minimizing such distortions. These questions are the primary focus of the present study.

In the course of examining texture for the present study, it became clear that the concept of texture as it appears in the literature is rather broad. Sometimes it simply refers to the mere presence of texture (as opposed to it absence). Other times it refers to the density of or frequency of the elements (e.g., trees per unit area) (DeMaio et al., 1983). More recently, researchers have begun to study some more subtle differences between sources of texture information (Kleiss and Hubbard, 1993). For the distant task, we examined two aspects of texture: (1) its presence versus its absence; and (2) the size and frequency of its elements (larger elements equate to lower frequencies).

Pattern type. To determine if the effects of texture vary with the type of pattern selected, we use two different pattern types in our research. The first pattern is a continuous pattern consisting of interlocking elements. The second pattern is intermittent in that the elements of the pattern did not touch one another. That is, the elements of the pattern are evenly spaced on a homogeneous background. For each pattern type, the size of the elements comprising the pattern vary according to the level of texture presented.

Effects of object size. A third cue of interest to us in the distant task is relative size of objects. The effectiveness of this cue in a VE has been previously shown to vary as a function of distance at ranges of one to two meters (Surdick, et al., 1994). It is unclear what affect this cue will have at greater ranges.

Distant task hypotheses. The following hypotheses are based on our review of the literature and our experiences in using virtual environments.

1. In general, subjects will underestimate distances. This is consistent with previous work on distance production in a VE (Wright, 1995).

2. Object size will affect estimates. All other things being equal, the larger object will be perceived as closer while the smaller object will be perceived as farther away.

3. Floor pattern will affect estimates. All other things being equal, the continuous (bone) pattern will cause subjects to perceive the cylinder as farther while the intermittent (dot) pattern will cause subjects to perceive the cylinder as closer.

4. Floor texture will affect estimates. All other things being equal, high frequency floor patterns will cause subjects to perceive the cylinder as farther, while the low frequency floor patterns will cause subjects to perceive the cylinder as closer. It is expected that the absence of texture (control) will cause subjects to perceive the cylinder as closer than both the high and low frequency textures. This hypothesis is based on the notion that increases in the number of perceptual events occurring between the observer and the target will increase perceived distance to the target.

Proximate Task

This task requires a stationary observer to view a static surface at near distances (i.e., 1 to 12 feet) and estimate the distance from themselves to the surface. Accurate estimation of such distances is important for avoiding collisions with walls and doorways in a VE.

The cues most relevant for this task are expected to differ from those germane to the distant task. At near ranges, one would expect pictorial cues to decrease in importance while system induced and physiological cues become more important. At near ranges, stereopsis would be expected to be an important physiological cue. Patterson, Moe, and Hewitt (1992) have previously explored several aspects of stereopsis in imaging displays. Therefore, stereopsis was not investigated in the present study and was held constant across all conditions.

Effects of reducing the field of view (FOV). A system induced cue of interest in the proximate task is FOV. The reduced FOV characteristic of VE's has been studied by researchers for its effect on the sense of immersion (Furness, 1992; Howlett, 1990) and on simulator sickness (Jex, 1991). More recently, Psotka et al.(1993) have examined the incongruence of geometric FOV and display FOV as a determinant of the observer's perceived egocenter position. The results, however, did not clearly demonstrate an effect of FOV on distance estimation.

It is likely that a reduced FOV can interact with task demands (in this case estimating near distances) to affect the importance of different depth cues. In a VE to real world transfer study, Witmer et al. (1994) reported frequent collisions with walls and doorways as subjects moved through the VE. A possible explanation for this stems from the reduced FOV. For example, as an individual approaches a turn in a corridor or other wall, the limited FOV causes them to lose sight of the contours (i.e., perspective cues) provided by the intersection of wall and ceiling, wall and floor, or wall and wall. Once these contours pass beyond the edges of the FOV, the effect is often that of viewing a blank field which provides almost no depth cues. The observer can no longer tell how far they are from the wall. If a larger, more natural FOV were provided, the important perspective cues would pass into the periphery of the FOV, but would still be available for judging distance to the surface.

Importance of texture. By causing perspective cues to disappear prematurely, a reduced FOV acts to increases the effectiveness of the cues that remain, such as texture. This is consistent with the weighted additive model of depth perception discussed by Wickens et al.(1989). Simple virtual environments which make little use of texture provide few cues for depth other than linear perspective. Hence the reduction or elimination of linear perspective cues resulting from a reduced FOV significantly diminishes the accuracy of distance judgements in these environments. The thoughtful application of texture to walls or other surfaces might help to improve distant judgements in VEs.

Gibson (1979) has described a hierarchy of detail that emerges as one changes one's altitude. This progressive detection of more or less detail as a function of distance (from the ground) has been termed nested or emergent texture. Reardon and Warren (1989) have suggested that it may be an important cue in landing an aircraft, a task requiring very accurate distance judgement. Weinstein (1989) found improved landing performance for structured texture (e.g., equidistant dots or checkerboard) over random texture (e.g., random dots). All of these types of texture (i.e., structured, emergent, nested) appear to afford something that random texture does not. Specifically, they provide detectable, consistent changes in appearance that vary with small changes in distance. Presumably, the enhanced detectability of small changes in distance provided by emergent textures would make them well suited for the proximate task. That is, judging small changes in distance (from a wall) at close ranges (1-12 feet). Thus due to its clear relevance to the proximate task we examined the role of emergent texture in the present study.

Proximate task hypotheses. The following hypotheses are based on our review of the literature and our experiences in using virtual environments.

1. In general, subjects will underestimate distances. This hypothesis is consistent with previous work on distance production in a VE (Wright, 1995).

2. Field of view will affect estimates. The reduced FOV will cause subjects to perceive the wall as being farther relative to the full FOV.

3. Wall pattern will affect estimates. The rich emergent pattern will result in more accurate distance estimates relative to the poor pattern.

4. The resolution of a textured wall pattern will affect distance estimates to the wall. A high resolution texture will result in more accurate distance estimates than a low resolution texture. A low resolution texture will result in more accurate distance estimates than the untextured wall.

Experiment 1. Distant Task

Method

Participants. The participants were 24 students enrolled in classes at the University of Central Florida. Half of the participants were men and half were women. All participants had 20/20 vision uncorrected or corrected with contact lenses and reported no other vision problems.

Materials. The virtual environment (VE) was modeled using Multigen and rendered by a Silicon Graphics Crimson Reality Engine. Performer provided the operating software and the VE was displayed on a Fakespace Labs^{tm} BOOM2C display. The BOOM2C is a high resolution stereoscopic display, that presents approximately 1280 x 1024 pixels per eye in the monochrome mode. The BOOM2C CRT display is attached to a mechanical arm that counterbalances the display and allows head tracking. The maximum display field of view is 140 degrees horizontally and 90 degrees vertically. The user's head position and orientation is normally tracked in three dimensions by position sensors located at six joints on the mechanical arm. To eliminate motion parallax cues, the tracking was turned off for this research.

The research was conducted in a small cubicle sized chamber at the Institute for Simulation and Training. In the chamber were a desk with a computer terminal and a color monitor. The simulation was controlled from the terminal and the virtual environment was displayed both on the monitor and on the BOOM2C. Participants made their distance judgements while seated on a 3.5 foot high wooden stool positioned in front of the BOOM2C display.

A long corridor outside of the experimental chamber was used to examine the ability of participants to estimate real world distances. The corridor was approximately 150 feet long, and measured 10 feet wide by 12 feet high. The corridor had numerous doors leading to offices, and an intersection with another corridor at a distance of approximately 50 feet from the participant. The floor of the corridor was covered with unpatterned carpeting.

Real world estimates used a black cylinder made of heavy construction paper, 2.5 feet high and 2.5 feet in diameter, and an electronic stop watch for timing judgement latencies. A clipboard was used for recording manually the real world judgements.

The Immersive Tendencies Questionnaire (ITQ) and Presence Questionnaire (PQ) were used for measuring presence (Witmer & Singer, 1994). The Simulator Sickness Questionnaire (SSQ) was used for measuring simulator sickness (Kennedy, Lane, Lilienthal, Berbaum, & Hettinger, 1992). These questionnaires are routinely administered in conjunction with our VE research. A post-experiment questionnaire was also used to assess the degree to which participants relied on different perceptual cues in making their distance judgements. Participants were asked to list any cues used in making their distance estimates and rate these against a list of cues suggested by the experimenter. Distance cues were rated in terms of their frequency of use on a 5-point Likert scale. After rating the cues participants ranked them in order of how much they used each cue. A demographics form was used to record age and gender and to screen for vision problems.

The virtual environment. A simple virtual environment was developed specifically for the purposes of this experiment. The VE consisted of a 130 foot long corridor terminated by a wall at the far end. The corridor was 10 feet wide by 10 feet high. The observer's eyepoint was positioned at 120 feet from the far wall of the corridor and 5.5 feet above the floor. The observer's eyepoint was held at this position throughout the experiment.

The software allowed the experimenter to select an object and position it at various distances along the corridor. The objects to which subjects were to estimate distances were two black cylinders resting on the floor of the corridor. The smaller of these cylinders was 2.5 feet in diameter and 2.5 feet tall while the larger of these was 5 feet in diameter and 5 feet tall. The software also permitted the experimenter to select from six different floor textures.

Two pattern types (continuous and intermittent) were combined with three pattern textures (fine, coarse, and control) to produce the floor designs shown in Figure 1. The continuous patterns were shaped like a bone while the intermittent patterns were circular or dot shaped. The elements (dots or bones) comprising the coarsely textured patterns were twice the size of the elements comprising the finely textured patterns. The control version of each pattern type was transparent (i.e., blank). In describing the results of this experiment and in subsequent discussion, the pattern type will be referred to simply as *pattern* or *floor pattern*, and the size of the elements in the pattern will be referred to as *texture* or *floor texture*. The VE was displayed in monochrome in varying shades of green and black. Slightly different shades of green on the floor, walls, and ceiling made each easily distinguishable from the others. The walls and ceiling were not textured.

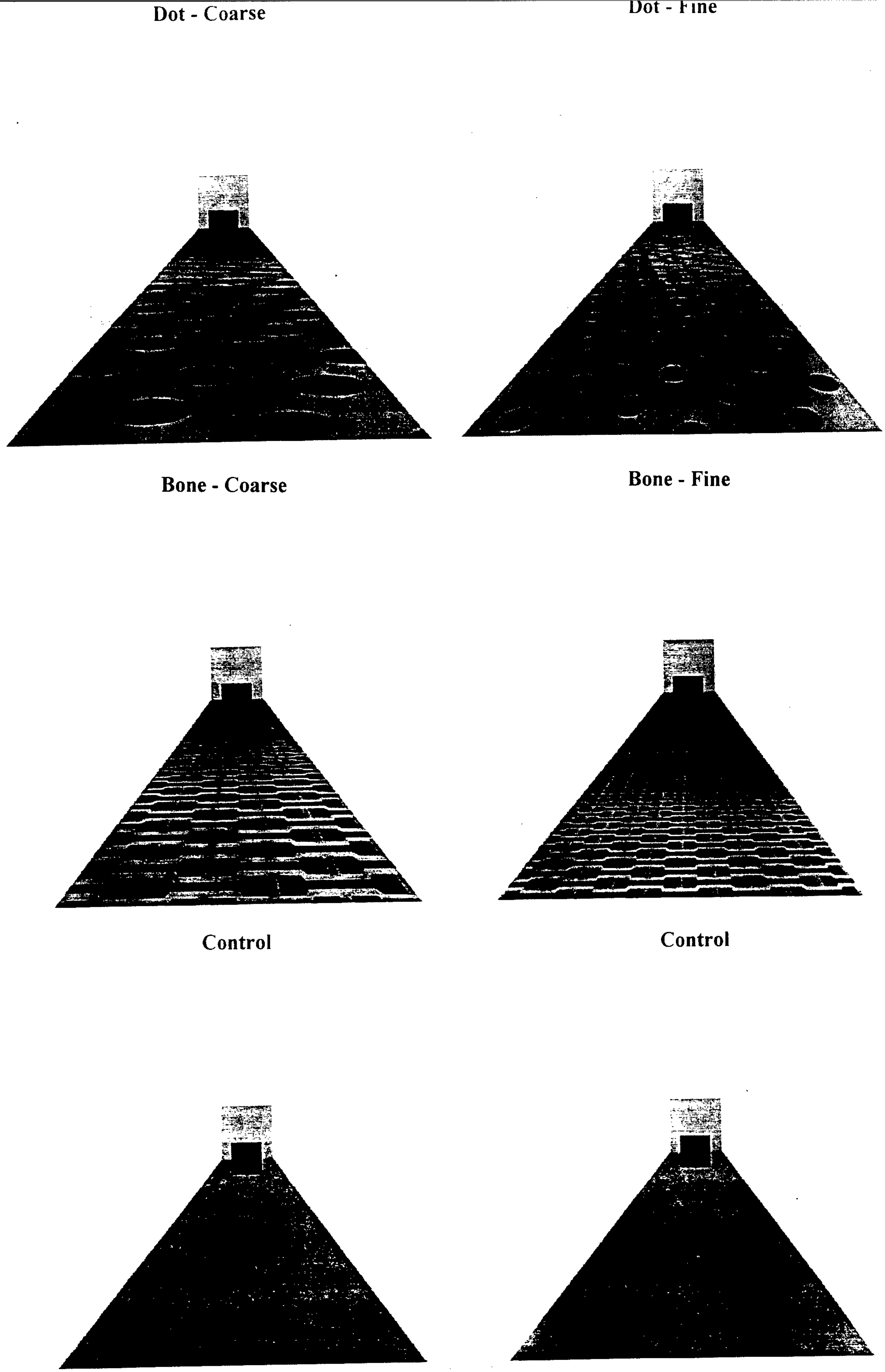

Figure 1. Floor designs

Procedure. Participants were briefed regarding the purpose of the research and what they would be expected to do. Then they completed ITQ and SSQ questionnaires. Participants then received instructions describing the distance estimation task, to include a description and an example of magnitude estimation. They then were seated on the stool in front of the BOOM2C display and completed six practice trials to familiarize them with the task requirements. Following practice they estimated distance to the cylinders on each of 36 trials, followed by a short break, then estimated distances on another identical set of 36 trials.

On each trial, a 2-second warning flash was presented signaling the beginning of the trial. After 2 seconds, the scene of the corridor then appeared with a cylinder appearing at one of six distances (10, 30, 50, 70, 90, or 110 feet). From the participant's perspective, the distance at which the cylinder appeared on any given trial was random. Participants viewed the scene for 5 seconds; then a beep sounded signaling that the participant should report their estimate of the distance to the cylinder. Following the beep, five additional seconds were allowed for reporting the distance before the scene disappeared. When participants reported their estimates, the experimenter recorded their response latency and distance estimate. Following a fixed intertrial interval of 10 seconds, the next trial was presented.

Floor pattern, texture, and cylinder size were varied in a counterbalanced fashion across the two replications of 36 trials. All participants received each pattern type, pattern size, cylinder size combination at each of the six distances. The order of distances to be estimated was determined by a 6x6 Latin square arrangement and was the same for all participants.

In estimating the distances, participants employed a magnitude estimation procedure using a modified free modulus technique. In this procedure, a standard (modulus) is presented for which the subject makes an estimate. No feedback is provided regarding the accuracy of this estimate. Instead the subject is instructed to make all subsequent estimates relative to this first estimate. For example, if the first stimulus was rated as 10 and another stimulus appeared to be twice as far, that stimulus should be rated as 20. Participants were instructed to make all estimates in terms of feet, a hopefully familiar unit of distance. While we expected individual participants to differ in their concept of a foot, we believe that each individual's concept of a foot should be more stable than their concept of an unnamed arbitrary unit of distance. Thus, the use of a familiar unit (i.e., feet), should help to make this abstract procedure more concrete and easier for the participants to understand.

After completing the experimental trials, participants completed the SSQ, the PQ, and a post-experiment questionnaire. The post-experiment questionnaire was designed to determine which perceptual cues the subjects used in making their distance estimates. After completing the questionnaires, participants followed the experimenter to the real-world corridor located just outside of the experimental chamber, and were seated on a stool identical to that used in the virtual environment phase of the experiment.

The real world trials were conducted in an attempt to assess the participants' ability to estimate distances in a natural real-world setting. Participants were instructed to follow the same procedures that they had used in the virtual world in estimating distances to a cylinder in the real world. The only procedural difference was that participants sat with their backs to the cylinder until signaled by the experimenter to turn and face the cylinder. Upon reporting their estimate of the distance, participants turned with their back again to the cylinder. This procedure ensured that the participants did not see the cylinder while it was being moved from one location to the next and limited their viewing time. This set up a situation that was roughly analogous to the situation in the VE.

Participants were given six practice trials in the real world followed by twelve test trials. At the beginning of each trial, one experimenter positioned the cylinder on the floor at one of six distances from the participant. The distances, 10, 30, 50, 70, 90 and 110 feet, were presented twice in the same random order to all participants. When the cylinder was in place, a second experimenter told the participant to turn and face the cylinder. After viewing the cylinder for five seconds, the participant heard a beep from a electronic stopwatch operated by the second experimenter. The participant then reported the distance within a 5-second interval following the beep. Upon reporting the distance, participants were instructed to turn their back to the cylinder while the first experimenter moved it to a new location along the corridor. For each trial the distance estimate and the response latency following the beep were recorded.

Experiment 1 Design. The experimental design is a pattern size (3 levels) x cylinder size (2 levels) x distance (6 levels) all within repeated measures design and is outlined below. The basic design shown in Table 1 below is replicated for each of two pattern types, a continuous pattern and an intermittent pattern. One between subjects variable, gender (2 levels), was also investigated.

Table 1.

Experiment 1 Design

Pattern Size	Cylinder Size: Small (2.5ft diameter)	Large (5ft diameter)
Control(none)	D1,D2,D3,D4,D5,D6	D1,D2,D3,D4,D5,D6
Fine	D1,D2,D3,D4,D5,D6	D1,D2,D3,D4,D5,D6
Coarse	D1,D2,D3,D4,D5,D6	D1,D2,D3,D4,D5,D6

Data Analyses. The magnitude estimates for each subject were used to determine a linear regression function relating log actual distance to log estimated distance. The slope of this function is the exponent of the power function ($S=kI^n$). The exponent of this function provides an indication of the consistency of the estimates.

Inspection of the data revealed markedly skewed distributions for all of the dependent measures. Therefore, the data were transformed using a Log(x+1) transformation to normalize the data before assessing the effects of the independent measures. Following transformation, two MANOVAs were performed. The first used the distance estimates and response latencies as the dependent measures, while the second used error in the estimates and latency as dependent measures. Gender, pattern type, texture (size of pattern elements), relative size of the cylinder, and distance were the independent variables in both analyses. The measure of error used in these analyses is the relative error, which represents the percent error in an estimate, with the sign indicating the direction of the error. The following formula was used to compute the relative errors.

Relative Error = (Estimate - Viewing Distance)/Viewing Distance

Significant main effects revealed by these MANOVAs were followed by individual ANOVAs for each dependent variable. Selected post hoc contrasts were also performed.

Results

Factors affecting distance estimates in VE. Table 2 summarizes the results for the distant task. Asterisks denote statistically significant effects. The MANOVA using distance estimate and latency as the dependent measures revealed significant main effects for cylinder size, F (2,21) = 18.52, p = .000, texture F(4,19) = 3.80, p = .02, and for distance, F(10,13) = 91.79, p = .000, but not for gender or pattern. None of the interactions were significant. The MANOVA using relative error

Table 2

Distant Task Summary of Results

Effect	MANOVA Estimate & Latency	MANOVA Relative Error & Latency	ANOVA Estimate	ANOVA Latency	ANOVA Relative Error
Gender(G)	0.832	0.826	0.57	0.972	0.566
Texture (T)	0.02*	0.026*	0.064	0.733	0.014*
Pattern (P)	0.433	0.433	0.665	0.202	0.157
Obj Size (S)	0.001*	0.001*	0.001*	0.901	0.002*
Distance (D)	0.001*	0.005*	0.001*	0.136	0.003*
TxP	0.291	0.315	0.081	0.746	0.001*
TxD	0.468	0.415	0.423	0.039*	0.001*
PxS	0.296	0.297	0.423	0.115	0.001*
PxD	0.985	0.975	0.999	0.723	0.001*
SxD	0.068	0.063	0.013*	0.708	0.001*
GxTxD	0.454	0.303	0.183	0.525	0.046*
TxPxS	0.58	0.476	0.881	0.288	0.001*
TxPxD	0.539	0.471	0.161	0.183	0.001*
TxSxD	0.898	0.837	0.944	0.521	0.001*
PxSxD	0.859	0.906	0.847	0.94	0.001*
TxPxSxD	0.569	0.491	0.208	0.316	0.001*
GxTxPxSxD	0.534	0.417	.046*	0.872	.03*

and latency produced the same pattern of results, although the p-values differed slightly. The p-values for all of the analyses are presented in Table 2. MANOVAs were followed by ANOVAs for each dependent variable. Significant main effects for cylinder size, $F(1,22) = 38.67$, $p = .000$, and distance, $F(5,18) = 192.25$, $p = .000$, were found for the magnitude of the estimates. Similarly, significant effects for cylinder size, $F(1,22) = 12.41$, $p = .002$, and distance, $F(5,18) = 5.60$, $p = .003$, were found for relative error. The estimates were more accurate for the small cylinder than for the large cylinder. In addition, a significant effect for texture, $F(2,21) = 5.25$, $p = .014$, was also found for the relative error measure. Estimates were more accurate when the fine texture or no texture was used than when the coarse texture was used. Cylinder size and distance interacted to significantly affect the magnitude of the estimates, $F(5,18) = 3.97$, $p = .013$, while texture and distance interacted to influence the latency of the estimates, $F(10,13) = 2.87$, $p = .039$. Numerous significant interactions were found for the relative error measure as shown in Table 2. Some of these interactions were difficult to interpret, and graphing them did little to assist in their interpretation. Others were simply of little interest. Two interesting interactions that could be unambiguously interpreted include a significant pattern by texture interaction, $F(2,21) = 28.27$, $p = .000$ and a significant cylinder size by distance interaction, $F(5,18) = 7.64$, $p = .001$. These interactions are depicted graphically in Figures 2 and 3, respectively. Figure 2 suggests that certain combinations of pattern and texture produce more accurate estimates than do others. A test of simple effects revealed that the subjects underestimated distances significantly less (more accurate) with the fine bone pattern than with the fine dot pattern, $P < .02$. This test of simple effects also revealed a significant overall effect of texture for the bone pattern, $p < .02$, but not for the dot pattern. Figure 3 shows that the percentage error in distance judgements (i.e., the relative error) is generally greater when the distances to be judged are greater. The one exception to this rule seems to be for the large cylinder at 10 feet. The data displayed in Figures 2 and 3 have been transformed using a Log(Relative Error + 1) transform. A Log(Relative Error + 1) of 0.3 corresponds to a relative error of -50%, while a Log(Relative Error +1) of 0.5 corresponds to a relative error of -68%.

Estimating distances in the virtual environment and in the real world. A direct comparison between the estimates made in the virtual environment and the true distances at which cylinders were viewed reveals that participants generally underestimated the distances to objects. Estimates in the VE typically were about 50% of the true distances. Our participants also underestimated distances to objects in the real world

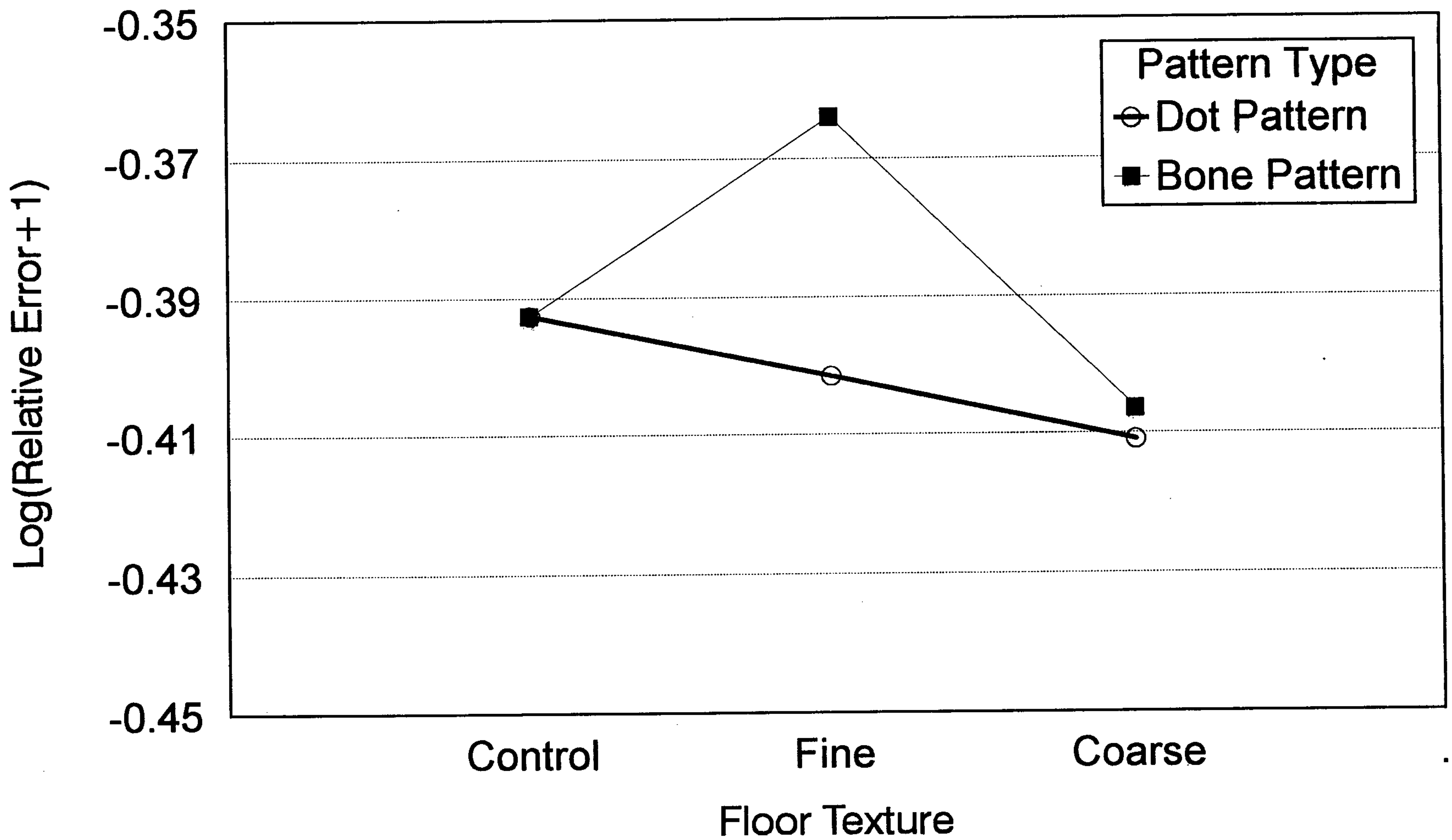

Figure 2. Texture by pattern interaction for relative error

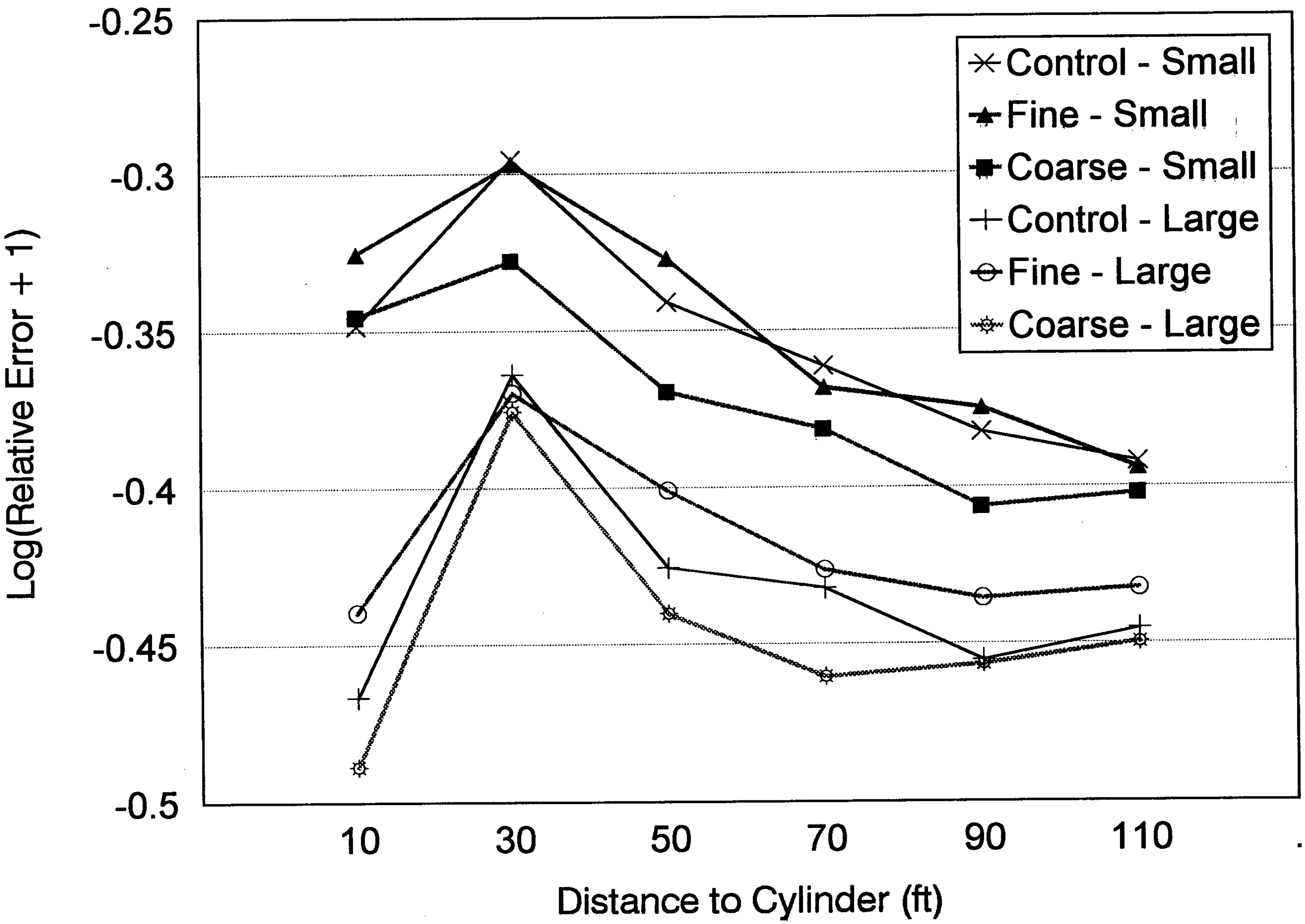

Figure 3. Effects of cylinder size and texture on relative error

environment, though to a lesser extent (about 75% of actual) than in the VE. Figure 4 shows the geometric means of the estimates in the VE and the real world as compared to the true distances. The geometric mean rather than the arithmetic mean was used to reduce the impact of outliers on the measure of central tendency. In figure 4, the top line shows the true distance to the cylinder, and hence represents perfect performance.

Post-experiment questionnaire. This questionnaire (see Appendix A) was designed to determine which perceptual cues the subjects used in making their distance estimates in the VE. It asked the participants to list the perceptual cues that they used in making their judgements. Participants then rated 'how much they used each cue', as well as others suggested by the questionnaire and present in the scene, on a 5 point Likert scale. An example of this scale is show below:

"During the experiment, how much did you use each of the following cues in making your judgements of distance (Circle a number for each)."

Cue A

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

After rating each of the cues, participants rank ordered the distance cues in terms of their importance for judging distance.

The responses to the Post-experiment questionnaire indicated that the participants utilized a variety of cues in rendering their distance judgements to include some of the manipulated variables, and other cues, such as the perceived width of the corridor, which were not varied systematically. Typically, participants gave their highest ratings to the distance cues that they had suggested (M = 3.65, SD = 1.16). For example, several participants estimated the distance to the mid point of the corridor or to the end of the corridor and used that distance as a referent. One participant reported using "the height of a small girl" as a yardstick to estimate the distance to the object. Of the experimenter suggested cues, participants reported using the perceived size of the object (M = 3.17, SD = 1.12) as a cue for distance more than any other cue. Other cues used frequently by participants include the floor pattern (M = 2.83, SD = 1.34), the perceived width of the corridor (M = 2.54, SD = 1.41), and the intersection between the object and the floor (M = 2.25, SD = 1.15). The width of the corridor appears to narrow as the object is placed at greater distances; this cue is commonly known as linear perspective and is an important cue for depth.

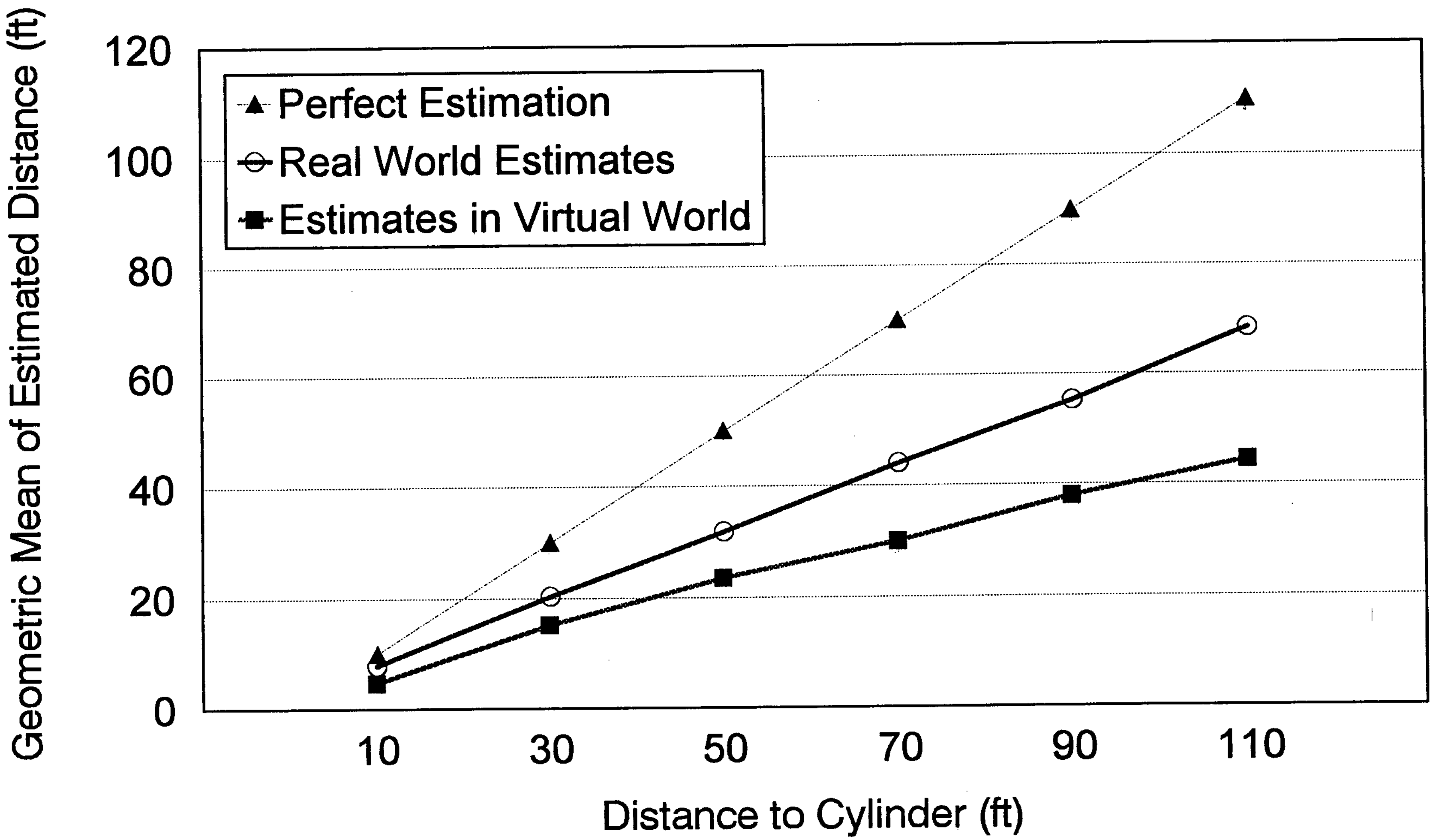

Figure 4. Geometric means of distance estimates in virtual and real world environments (small cylinder)

Some participants reported using cues in the real world which were not available in the VE. For example several participants reported estimating the distance between office doors and counting the number of doors between their position and the position of the object. There were no doors to count in the VE corridor.

Presence and Immersive Tendencies Questionnaires. The amount of presence reported in this experiment was low relative to previous experiments where subjects moved through the VE. For this experiment, the PQ scores ranged from 43 to 93 (M = 70, SD = 13.677), and the ITQ scores ranged from 49 to 95 (M = 72, SD = 12.63). The ITQ and PQ scores were not significantly correlated.

Simulator Sickness Questionnaire. No severe simulator sickness was reported in this study. The total simulator sickness scores ranged from 0 to 44.8 (M = 13.09, SD = 13.69). Subscale scores for Nausea subscale (M = 9.14, SD = 11.07), the Oculomotor Discomfort subscale (M = 15.16, SD = 16.12), and the Disorientation subscale (M = 7.54, SD = 11.59) also indicated few symptoms.

Power law exponents. Power law exponents (Stevens, 1986) for distance estimation in the VE are shown in Table 3 for various combinations of object size and floor texture. Pattern type was not used in computing power law exponents because it was not found to significantly affect the distance estimates. The exponents displayed in Table 3 vary from a low of .93 to a high of 1.01. An exponent of 1.0 indicates that the distance judgement is exactly proportional to the true distance.

Table 3
Steven's Power Law Exponents for Distance Judgements in VE as a Function of Object Size and Floor Texture

Floor Texture	Small Cylinder	Large Cylinder
None	.95	1.00
Fine	.97	.99
Coarse	.93	1.01

Because no variables were manipulated for the estimates made in the real world, only a single exponent was calculated. The exponent for real world estimate using a small cylinder as the object was .90.

Discussion

Corroborating the findings of Wright(1995) and Lampton, et. al,(1995), our subjects generally underestimated distances to the cylinders in the VE and in the real world. This finding supports our first hypothesis. The errors in distance estimation were found to be greater in virtual environments than in the real world. Real world performance tends to be better because more cues for depth are available in the real world. In VE, cylinder size had a greater effect on the distance estimates than did floor texture. As hypothesized, the larger cylinder was perceived as closer, while the smaller cylinder was perceived as farther away. Cylinder size may also have been responsible for large relative errors in judging objects at 10 feet (see Figure 3). The large cylinder viewed from a distance of 10 feet may have appeared so large relative to the large cylinder at other distances that the subjects may have perceived it to be much larger and therefore much closer than it actually was, resulting in gross underestimates at that distance. This looming effect is likely the reason why relative errors are much larger at 10 feet than at 30 or even 50 feet. Differences in relative errors at 10 and at 30 feet were much less pronounced when the smaller object was used, indicating a smaller looming effect. Decreasing object size should compensate in part for the tendency of observers to underestimate distances in VE. As hypothesized, texture significantly affected distance judgements, but results did not completely support our hypotheses. As predicted, subjects perceived the cylinders as farther when the high frequency floor textures (i.e, fine texture) were present than when the low frequency floor textures (i.e., the coarse texture) were present. But contrary to prediction, the control (i.e., no texture) condition did not consistently result in shorter perceived distances than the textured floor patterns. Also contrary to prediction, the type of floor pattern per se did not significantly influence the distance estimates, but instead interacted with texture to affect the distance estimates. The longest (and therefore most accurate) distance estimates in VE were found when the fine texture was combined with the continuous (bone) pattern. While this result is in the predicted direction, this best floor texture pattern combination compensated little for the gross underestimates of distance in VE.

The power law exponents calculated across the various experimental conditions revealed that subjects easily discriminated one distance from another in this experiment, despite the fact that the absolute distance estimates were not very accurate. That is, subjects reported objects as being farther away as the true distance to the cylinders increased. In fact, the estimated distances were almost exactly proportional to the true distances to the cylinders. The ease of discriminating among distances is evident from the results shown in Figure 4, where the geometric means of the estimates are shown to increase as the distances to the cylinders increase.

Experiment 2. Proximate Task

Method

Participants. Participants were 28 students enrolled in classes at the University of Central Florida. Half of the participants were male and half were female. All reported having 20/20 vision uncorrected or corrected with contact lenses and reported no other vision problems.

Materials. The hardware and software used in modeling and displaying the virtual environment (VE) was identical to that used in Experiment 1. As in experiment 1, head tracking was turned off. Subjects made their distance judgements while seated in the small chamber at the Institute for Simulation and Training. The ITQ, PQ, and SSQ questionnaires were administered as before. The post experiment questionnaire administered in this experiment was similar to the questionnaire administered in Experiment 1, but some of the items were different (see Appendix B). A brief demographics form was also used to record age and gender and to screen for vision problems.

The virtual environment. A simple virtual environment was developed specifically for the purposes of this experiment. The VE consisted of a 15 foot long corridor terminated by a wall at the far end. The corridor and far wall were 10 feet wide by 10 feet high. The observer's eyepoint was positioned 5.5 feet above the floor which approximates their real world eye height while seated on the stool. The observer's eye point always faced the far wall and was movable forward and back along the X-axis in 1 foot increments from the wall. The software allowed the experimenter to select a distance from the far wall and a pattern texture combination to be applied to the wall on each trial.

Two pattern types, rich and poor were combined with three pattern resolutions (also referred to as texture), fine, coarse, and control (none) to produce the six wall designs (see Figure 5 for illustrations of each). Three rich (emergent texture) patterns and three poor (non-emergent) patterns were available. Two fine (512 x 512 pixels), two coarse (16 x 16 pixels), and two control (no visible pixelation) pattern resolutions were available. These resolutions (512 and 16) were selected following extensive previewing by the experimenters. The VE was displayed in monochrome in varying shades of green and black. Slightly different shades of green on the floor, walls, and ceiling made each easily distinguishable from the others. The corridor walls, the floor and the ceiling were not textured.

Two levels of FOV, 140 degrees horizontal and 60 degrees horizontal were used in this experiment. The 140-degree FOV was provided by the BOOM display without restriction. The 60-degree FOV was achieved by use of a black polygon mask positioned approximately 10 inches forward of the observer's virtual eye point. A rectangular opening in the polygon mask allowed for a FOV of 60 degrees horizontal by 38.5 degrees vertical. This reduced FOV has the same 1.5 to 1 aspect ratio as the unrestricted BOOM display.

<u>Procedure</u>. Participants were briefed regarding the purpose of the research and what they would be expected to do. Then they completed demographic, ITQ, and SSQ questionnaires. After that they received instructions describing the distance estimation task, to include a description and an example of magnitude estimation. They then were seated on the stool in front of the BOOM2C display and completed six practice trials to familiarize them with the task requirements. Following practice, they estimated distance to the wall on each of 36 trials, followed by a short break, then estimated distances on an additional 36 trials. Half of the participants were tested with the restricted FOV; the other half judged distances with the full FOV.

On each trial, a 2-second warning flash was presented signaling the beginning of the trial. After 2 seconds, the scene of the corridor then appeared with the observer's virtual body positioned at one of 12 distances from the wall (1,2,3,4,5,6,7,8,9,10,11,12 feet). From the participants' perspective, the distance at which they were positioned relative to the wall varied randomly from one trial to the next. As in Experiment 1, participants had a 5-second viewing interval, a beep signaling the start of a 5-second response interval and a 10-second intertrial interval.

Combinations of wall pattern and texture resolution were randomly presented across the 72 trials. All participants received each wall pattern type, texture resolution combination at each of the twelve distances. The distances to be estimated were also ordered randomly across subjects. In estimating the distances, participants employed a magnitude estimation procedure using a modified free modulus technique.

After completing the experimental trials, participants completed the SSQ, the PQ, and a post-experiment questionnaire. After completing the questionnaires, participants were debriefed, paid or assigned extra credit, and released

<u>Data Analyses</u>. The magnitude estimates for each subject were used to determine a linear regression function relating log actual distance to log estimated distance. The slope of this function is the exponent of the power function ($S=kI^n$). The combination of the exponent and the Y intercept of this function provide an indication of the consistency and accuracy of the estimates in relative terms.

Inspection of the data revealed markedly skewed distributions for all of the dependent measures. Therefore, the data were transformed using a Log(x+1) transformation to normalize the data. Following transformation, two MANOVAs were performed. The first used the distance estimates and response latencies as the dependent measures, while the second used error in the estimates and latency as dependent measures. Gender, display field of view, pattern type, resolution of the pattern or texture, and distance were the independent variables in both analyses. The measure of error used in these analyses is the relative error. Significant main effects revealed by these MANOVAs were followed by individual ANOVAs for each dependent variable. Selected post hoc contrasts were also performed.

Results

Factors affecting distance estimates in VE. Table 4 summarizes the results of this experiment, showing the p-values for each effect for the various analyses. Asterisks denote statistically significant effects. The MANOVA that included distance estimate and latency as the dependent measures revealed significant main effects for FOV, $F(2,23) = 5.68$, $p = .01$, and for distance, $F(22,3) = 17.63$, $p = .018$, but not for gender, texture, or pattern. Significant texture by distance, $F(44,1054) = 5.28$, $p = .000$, and pattern by distance, $F(22,3) = 8.67$, $p = .05$, interactions suggests that texture and pattern affects distance estimates at some distances but not at others. Significant interactions of texture, pattern, and distance with FOV, $F(44,1054) = 1.80$, $p = .001$, suggests that texture and pattern effects may depend both on distance and on FOV. The MANOVA using relative error and latency produced a main effect only for FOV, $F(2,23) = 5.85$, $p = .009$. Significant interactions between texture and distance, $F(44,1054) = 2.53$, $p =.000$, and pattern and distance, $F(22,3) = 14.1$, $p = .025$, were obtained as before. A significant FOV by texture by distance interaction was also obtained, $F(44, 1054) = 2.50$, $p = .000$.

MANOVAs were followed by ANOVAs for each dependent variable. Significant main effects for FOV, $F(1,24) = 11.54$, $p = .002$, pattern, $F(1,24) = 6.07$, $p = .021$, and distance, $F(11,14) = 48.92$, $p = .000$, were found for the magnitude of the estimates. The effects of FOV and distance are shown in Figure 6, and the effects of pattern across distance is shown in Figure 7. As was the case for the multivariate results, significant pattern by distance, $F(11,14) = 7.21$, $p = .000$, texture by distance, $F(22,3) = 9.80$, $p = .042$, and pattern by texture by distance interactions, $F(22,3) = 310.94$, $p = .000$, were obtained. FOV interacted with distance and texture to influence judgements as well, $F(22,3) = 17.48$, $p = .018$. The combined effects of FOV, distance and pattern are shown in Figure 8, and the combined effects of FOV, distance and texture are shown in Figure 9. These figures suggest that texture, and to a lesser extent pattern, become more important for accurate distance perception

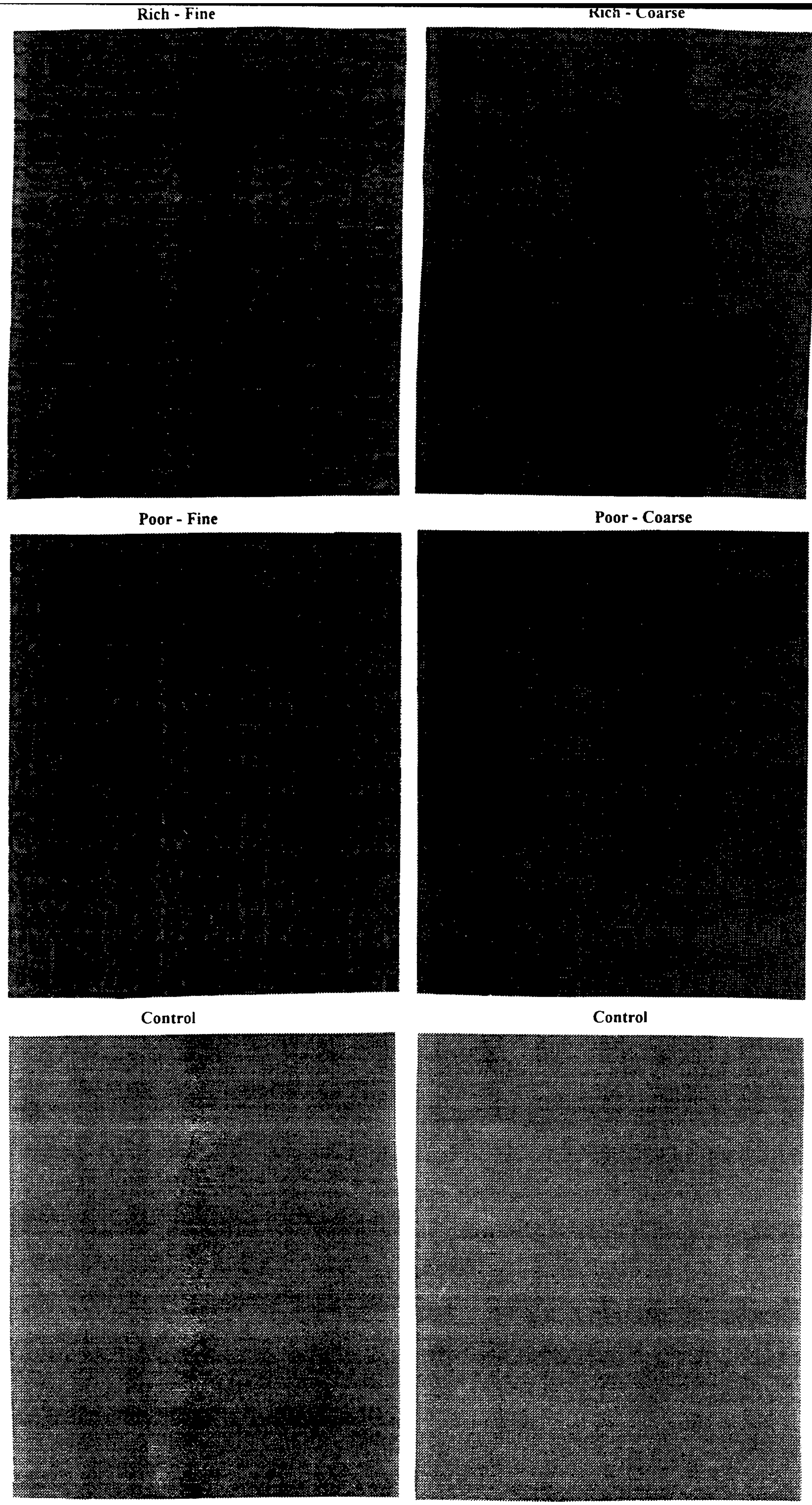

Figure 5. Wall designs

Table 4

Proximate Task Summary of Results

Effect	MANOVA Estimate & Latency	MANOVA Relative Error & Latency	ANOVA Estimate	ANOVA Latency	ANOVA Relative Error
Field of View (F)	.01*	.009*	.002*	0.12	.002*
Gender (G)	0.223	0.232	0.873	0.088	0.884
Texture (T)	0.347	0.553	0.469	0.217	0.294
Pattern (P)	0.051	0.553	.021*	0.359	0.567
Distance (D)	.018*	0.094	.001*	0.072	.001*
FxT	0.129	.039*	0.061	0.588	.012*
FxD	0.386	0.388	.001*	0.985	.009*
TxD	.001*	.001*	.042*	0.522	0.087
PxD	.05*	.025*	.001*	0.758	0.252
FxTxD	.001*	.001*	.018*	0.691	0.126
TxPxD	.001*	0.409	.001*	0.342	0.128
FxPxD	0.497	0.573	0.123	.020*	0.941
FxTxPxD	.001*	0.923	0.002*	0.741	0.127
GxFxTxD	0.743	0.513	0.056	0.584	.026*
GxFxTxPxD	0.068	.043*	0.114	0.343	0.908

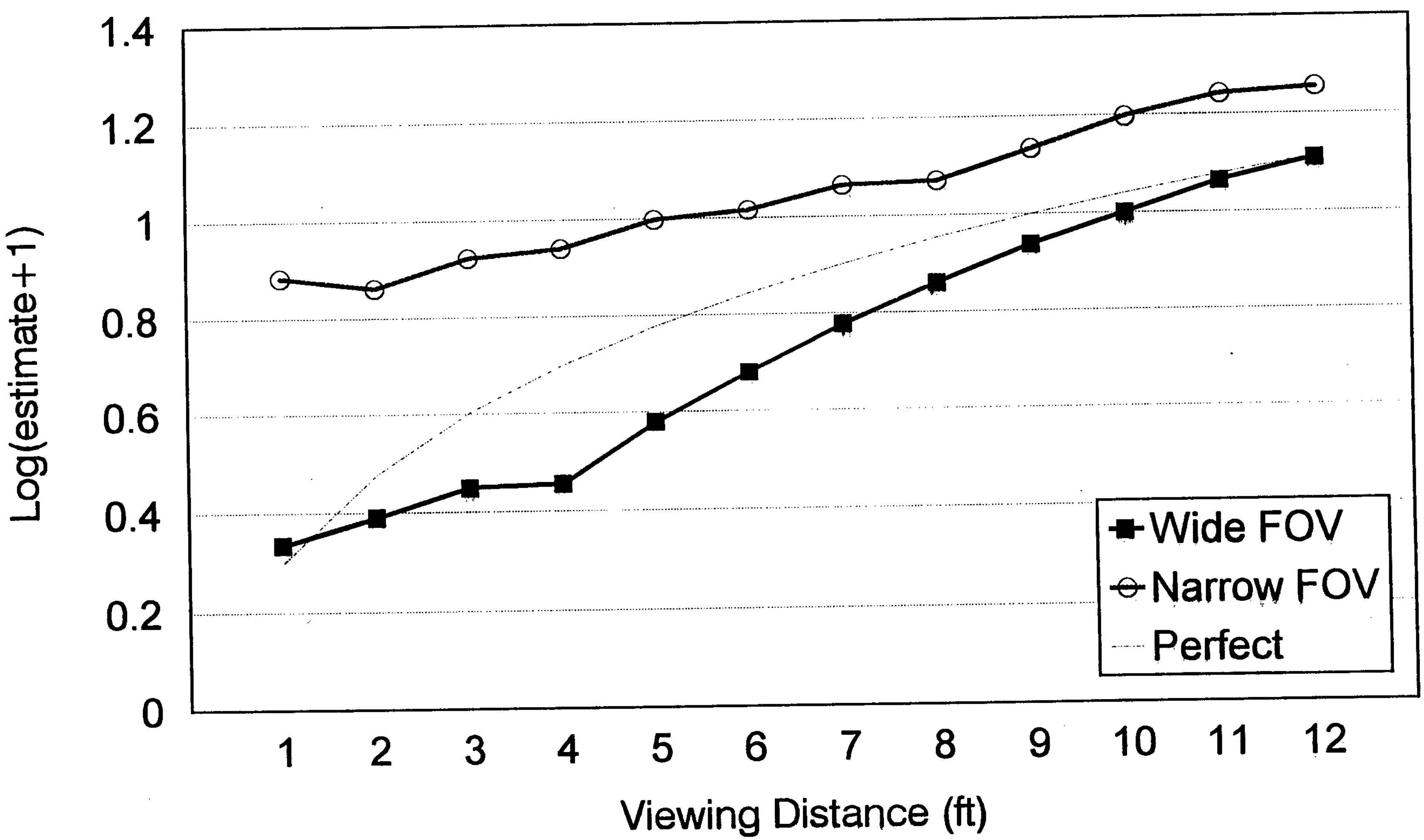

Figure 6. Distance estimates as a function of display FOV and viewing distance

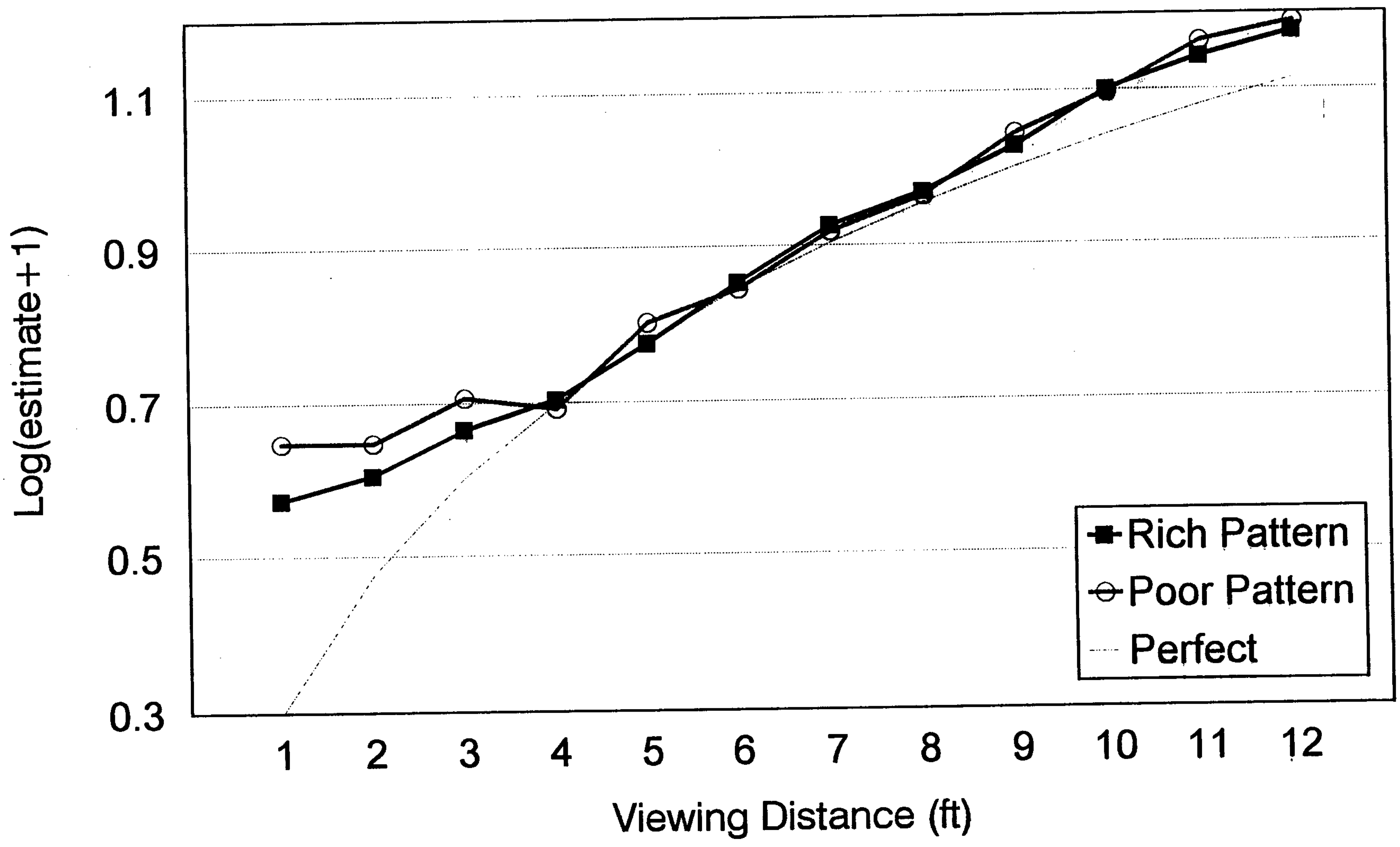

Figure 7. Distance estimates as a function of wall pattern and viewing distance

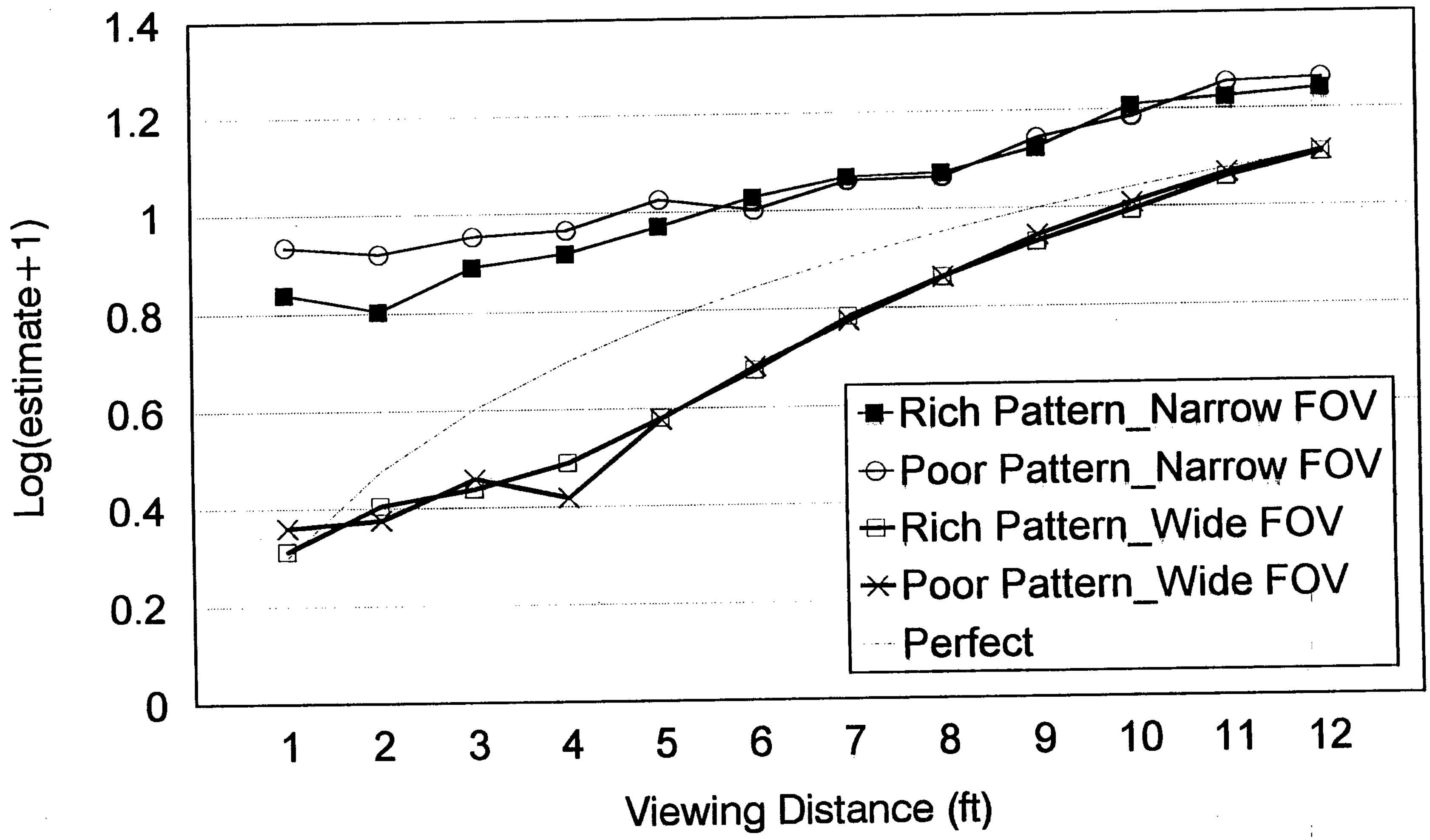

Figure 8. Distance estimates as a function of display FOV, wall pattern and viewing distance

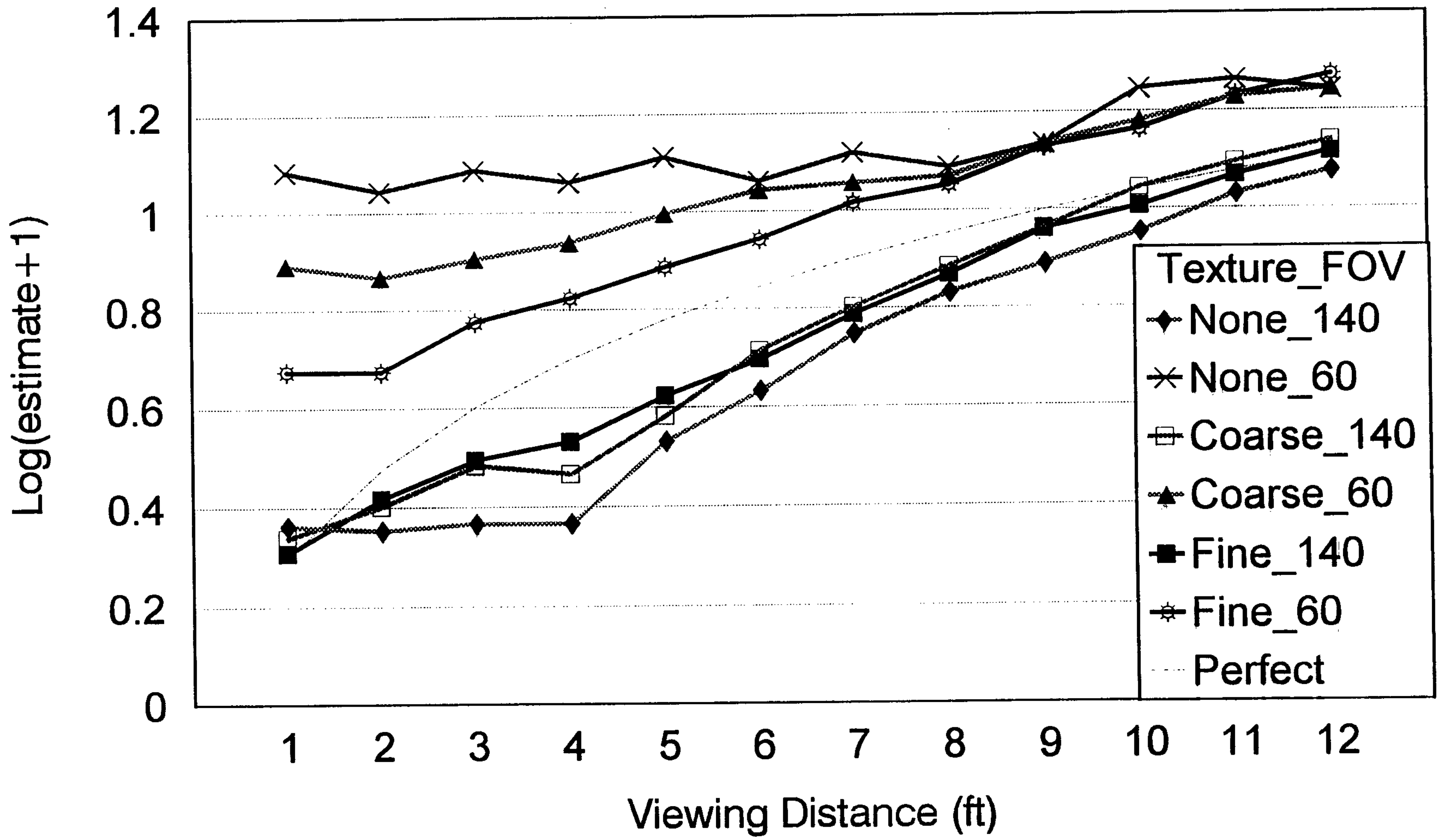

Figure 9. Distance estimates as a function of display FOV, wall texture, and viewing distance

when the field of view is restricted. Figure 9 also suggests that without texture, participants do not discriminate distances well among the closer distances. That is, they give approximately the same estimate at 4 feet as they do at 1 foot.

Significant main effects for FOV, $\underline{F}(1,24) = 84.63$, $\underline{p} = .002$, and distance, $\underline{F}(11,14) = 9.58$, $\underline{p} = .000$, were also found for the relative error measure. These effects are illustrated in Figure 10. The x-axis shown at zero indicates no judgement error, and hence represents perfect performance. The relative error was smaller, indicating more accurate judgements, for the wide FOV than for the restricted FOV. The relative error was also generally smaller at the longer distances than at the shorter distances. In contrast to results for the magnitude of the estimates, relative errors were not significantly affected by type of pattern used. The only significant interactions for the relative error measure were the the FOV by distance interaction, $\underline{F}(11,14) = 3.97$, $\underline{p} = .009$ and the FOV by texture interaction, $\underline{F}(2,23) = 5.4$, $\underline{p} = .012$. A test of simple effects on the FOV by texture interaction revealed a significant effect of FOV at each level of texture, $\underline{ps} < .02$. At each level, the wide FOV produced underestimates while the narrow FOV produced overestimates. This test of simple effects also revealed a significant effect of texture for the narrow FOV, $\underline{P} < .003$, but not for the wide FOV. A repeated measures ANOVA using only narrow FOV subjects indicated a significant main effect of texture, $F(2,24) = 4.39$, $p < .03$). Newman-Keuls range tests comparing the means of the three textures (i.e., control, coarse, fine) revealed that the overestimates for the control texture were significantly greater than for the fine texture, $\underline{p} < .02$. No other significant differences were detected among these means.

Latency was not very sensitive to the effects of our independent variables. The only significant latency effect was a FOV by pattern by distance interaction, $\underline{F}(11,14) = 3.26$, $\underline{p} = .02$.

Post-experiment questionnaire. This questionnaire (see Appendix B) was designed to determine which perceptual cues the subjects used in making their distance estimates in the VE. It asked the participants to list the perceptual cues that they used in making their judgements. Participants then rated 'how much they used each cue', as well as others suggested by the questionnaire and present in the scene, on a 5 point Likert scale. An example of this scale is show below:

"During the experiment, how much did you use each of the following cues in making your judgements of distance (Circle a number for each)."

Cue A

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

After rating each of the cues, participants rank ordered the distance cues in terms of their importance for judging distance.

The responses to the Post-experiment questionnaire indicated that the participants utilized a variety of cues in rendering their distance judgements. Cues included those listed independently by the subjects and cues suggested by the questionnaire items. Among those cues listed by the subjects were pattern size, pattern clarity, number of patterns visible, how much of the side walls, floor or ceiling was visible, and use their own body height as a yardstick. Typically, participants gave their highest ratings to the distance cues that they themselves had suggested ($\underline{M}$ = 4.0, $\underline{SD}$ = .82 for the wide FOV, and $\underline{M}$ = 4.17, $\underline{SD}$ = .41 for the narrow FOV). The most frequently reported cues by subjects with the wide FOV was how much of the floor or ceiling was visible. This suggests that many subjects were using linear perspective to judge distance on trials where it was available and using the absence of this cue on trials when it was not available. The cue listed most frequently by subjects with a narrow FOV was the clarity of the wall pattern. Cues suggested by the questionnaire items were typically rated lower than the cues suggested by the subjects. Of course there was some overlap in the two categories of cues (e.g., pattern size and pattern clarity). Of the questionnaire suggested cues, participants who had a wide FOV rated the perceived size of the wall as the most frequently used cue ($\underline{M}$ = 3.43, $\underline{SD}$ = .94). The second highest rated cue for the wide FOV was pattern size ($\underline{M}$ = 3.21, $\underline{SD}$ = 1.05). With a narrow FOV, the most highly rated cue was pattern clarity ($\underline{M}$ = 3.93, $\underline{SD}$ = .62), which is a function of the number of pixels in the pattern. The second most reported cue for distance was pattern size ($\underline{M}$ = 3.86, $\underline{SD}$ = .95). The ranks of the cues generally agreed with the ratings data, with wall size ranked as the most important cue with the wide FOV ($\underline{M}$ = 5.0, $\underline{SD}$ = 1.41) and pattern size as the most important cue for the narrow FOV ($\underline{M}$ = 5.36, $\underline{SD}$ = 1.98).

<u>Presence and Immersive Tendencies Questionnaires.</u> The amount of presence reported in this experiment was low relative to previous experiments where subjects moved through the VE. For this experiment, the PQ scores ranged from 45 to 82 ($\underline{M}$ = 64.21, $\underline{SD}$ = 9.06), and the ITQ scores ranged from 46 to 99 ($\underline{M}$ = 71.46, $\underline{SD}$ = 12.63). The ITQ and PQ scores were not significantly correlated. A t-test revealed that reducing the FOV from 140 to 60 degrees had no significant effect on PQ scores.

Simulator Sickness Questionnaire. No severe simulator sickness was reported in this study. The total simulator sickness scores ranged from 0 to 52.36 ($\underline{M}$ = 11.89, $\underline{SD}$ = 13.92). Subscale scores for Nausea subscale ($\underline{M}$ = 6.13, $\underline{SD}$ = 11.08), the Oculomotor Discomfort subscale ($\underline{M}$ = 12.99, $\underline{SD}$ = 15.83), and the Disorientation subscale ($\underline{M}$ = 11.43, $\underline{SD}$ = 14.20) also indicated few symptoms. Reducing the FOV from 140 to 60 degrees did not significantly affect total or subscale scores reported on the simulator sickness questionnaire. However the means were consistently higher for each of the three subscales when the narrow field of view was used.

Power law exponents. Steven's power law exponents for distance estimation in the VE are shown in Table 5 for various combinations of FOV and wall pattern and texture. The exponents displayed in Table 5 vary from a low of .14 to a high of 1.10. An exponent of 1.0 indicates that the distance judgement is exactly proportional to the true distance. Exponents calculated for the wide FOV were much closer to 1.0 than were exponents calculated for the narrow FOV. For the wide FOV, exponents varied between .90 and 1.10, whereas for the narrow FOV, exponents ranged from .14 to .50. The rich finely textured pattern produced the best results for the narrow FOV, which supports results obtained from the ANOVAs.

Table 5

Steven's Power law Exponents for Distance Judgements in VE as a Function of FOV and Wall Pattern and Texture

Pattern	Rich			Poor		
Texture	None	Coarse	Fine	None	Coarse	Fine
Wide FOV	.93	1.02	1.10	1.06	.89	.97
Narrow FOV	.14	.18	.51	.14	.21	.31

Relative magnitude of estimates. Figure 11 shows the geometric means of the distance estimates at near distances (1 to 12 feet) as a function of the FOV, and compares these mean estimates to the true distances. The dotted line shows true distance to the wall, and hence represents perfect performance. The estimates ranged from 32 to 99 percent of the true distances for the wide FOV, while the estimates ranged from 131 to 556 percent of the true distances for the narrow FOV. For the wide FOV, the distance estimates appear to be proportional to the true distances for distances greater than five feet, but not for distances less than that. The more accurate distance judgements at the longer distances likely reflect the presence of linear perspective cues. The figure provides some indication that the estimates are also proportional to the true distances for distances greater than seven feet with a narrow FOV, but not for distances less than that.

Discussion

Underestimation and overestimation of distance. We hypothesized that subjects would underestimate distance both in the wide and reduced FOV conditions, but underestimates were obtained only with the wide FOV.

Power law exponents and distance discrimination. The effects of a restricted FOV on distance estimates can be dramatic, as illustrated by the changes in the magnitude of Steven's power law exponents. With the wide FOV, the exponents were close to 1.0, indicating simple proportionality between the distance estimates and the true distances. With the narrow FOV, however, none of the exponents were close to 1.0, so that the estimated distances were proportional to the nth root of the true distances, where n varied between 2 and 7. The best performance with a narrow FOV was observed when a rich finely textured wall pattern was used; with this wall pattern, the estimated distances were proportional to the square root (n=2) of the true distances.

FOV and head tracking. One of the defining features of virtual environments is that they allow individuals to actively explore the environment by moving their head and body. In this experiment we did not allow our subjects to move either their head or body. We did this to eliminate motion related distance cues, such as motion parallax, motion perspective, and kinetic depth cues, which tend to dominate other depth cues. We were interested in identifying cues in VE, other than motion cues, that could be used to improve the accuracy of distance estimates in VE. By restricting head movement, we were also able to better control the FOV, allowing us to quantify precisely the effects on distance estimation of a reduced FOV. In previous research we found that individuals vary greatly in how much they move their heads. If we had not restricted head movement, subjects having a FOV of 60 degrees may have varied widely in the depth cues available to them because of individual differences in head movements.

In our research FOV was the most important determinant of the accuracy of estimating distances of 12 feet or less in the VE. The effects of FOV are consistent and unambiguous. In contrast to previous research (Lampton et. al, 1995), the effects of FOV were obtained using a single display device. Hence differences in resolution or other factors that vary among display devices are not possible confounds in this research. As clearly shown in Figure 6, subjects consistently overestimated distances in VE with a restricted FOV, whereas subjects having a wider FOV consistently underestimated the same distances. This result supports our hypothesis that a reduced FOV will cause subjects to perceive the wall as farther away relative to the full FOV.

Extrapolating from Figure 6, one might be tempted to conclude that if FOV had been a value somewhere in between 60 and 140 degrees, say around 100 degrees, then the estimates would have approached the true distances. While such a conclusion might seem reasonable at first, it would also probably be wrong. Depending on the distance at which linear perspective is lost for the 100 degree FOV, the amount of overestimation at the closest distances would likely be about the same as for the 60 degree FOV, while the underestimation at the longest distances would probably be about the same as for the 140 degree FOV.

The reduction or elimination of linear perspective is the probable cause of the discrepancy between distance estimates for the wide FOV and the narrow FOV. The elimination of linear perspective resulted in very poor distance discrimination up to distances of 8 feet for the control condition (i.e., no wall pattern or texture). Adding textured patterns to the wall at the end of the corridor enabled subjects to better discriminate between these distances, thus compensating somewhat for the restricted FOV. As predicted, the finely textured patterns compensated the most for the restricted field of view, improving the accuracy of distance estimates for distances less than 6 feet. While the coarsely textured pattern appeared to compensate some for the restricted FOV (see Figure 9), it did not significantly improve the accuracy of distance judgements over the control condition. These results suggest that the careful application of textures and patterns to walls or other objects may be essential for accurate depth perception and distance estimation when the display devices employed have a narrow FOV.

For the wide FOV, subjects failed to discriminate between distances from one to four feet, apparently because of the deficiency of linear perspective cues at these distances. The addition of a textured pattern to the wall, however, compensated for this deficiency resulting in improved distance discrimination. The compensatory effects of adding a textured pattern to the wall were less dramatic for the wide FOV than for the narrow FOV, however. Nevertheless, distance judgements were still positively affected by the addition of textured patterns when using a wide FOV, particularly at the closest distances. Our hypothesis regarding the effects of texture on distance estimates was not confirmed in the general sense. The effects of texture seem to depend on distance and FOV. However, as shown in figure 9, our hypotheses that fine textures would result in more accurate distance estimates than would coarse textures, and that both coarse and fine textures would produce more accurate estimates than no texture was supported, at least for the closer distances with the narrow FOV. Adding textured patterns should reduce the tendency to collide with objects in the VE because participants will be able to better judge when they are very close to the wall or object. Without textured patterns, and without sufficient linear perspective cues, subjects will grossly overestimate their distance from objects, increasing their chances of colliding with them.

Pattern richness and emerging patterns. In designing our simple virtual environments, we attempted to select one pattern (rich pattern) that would enable subjects to accurately discriminate distances between one and twelve feet, and another pattern (poor pattern) that would be an effective cue for distance only at the closest distances. Our rich pattern was designed to display emergent properties; the large branches in the foreground emerge from the background pattern at distances up to 12 feet, and the apparent size of the branches increases as the subjects are moved closer to the wall. Conversely, the small individual elements of the rich pattern background do not emerge at the longer distances and would only become a cue for distance when subjects were very close to the wall. At that point the background elements would begin to serve as a cue for distance as they grew in apparent size. The poor pattern, being identical to the background of the rich pattern, could be expected to be a useful cue for distance only at the closest distances. Hence, we expected that the rich and poor patterns would produce similar results at the closest distances with the rich pattern producing better estimates for the longest distances. Our subjects, however, did not appear to use these cues as anticipated, with the rich pattern being more effective than the poor patterns only at the closer distances. The failure of Ss to use emergent cues as anticipated may have been the result of the masking effects of linear perspective at the longer distances. Alternately the random ordering of the trials may have prevented subjects from recognizing the emergent properties of the patterns. That is, the subjects who viewed the various combinations of distance and wall pattern in a random order may not have realized that the size of the pattern elements were changing from trial to trial. While, our subjects did not use the cues provided by the rich pattern exactly as we expected, their distance estimates with the rich pattern were generally more accurate than with the poor pattern, providing marginal support for our hypothesis.

Uncontrolled distance cues. In this research linear perspective was not systematically manipulated, except as determined by the FOV. Otherwise it varied freely with distance, as did binocular disparity. Another uncontrolled cue for distance was stereopsis, as provided by the overlapping images in the BOOM display. These cues might have served as cues for discriminating and estimating distances. Each of these cues, when available, had the potential to mask the effects of pattern and texture on distance estimation. Despite this potential masking, significant effects were found for pattern and significant interactions were observed for both pattern and texture. The observed effects of FOV, however, were likely the result of changing linear perspective as an effective distance cue.

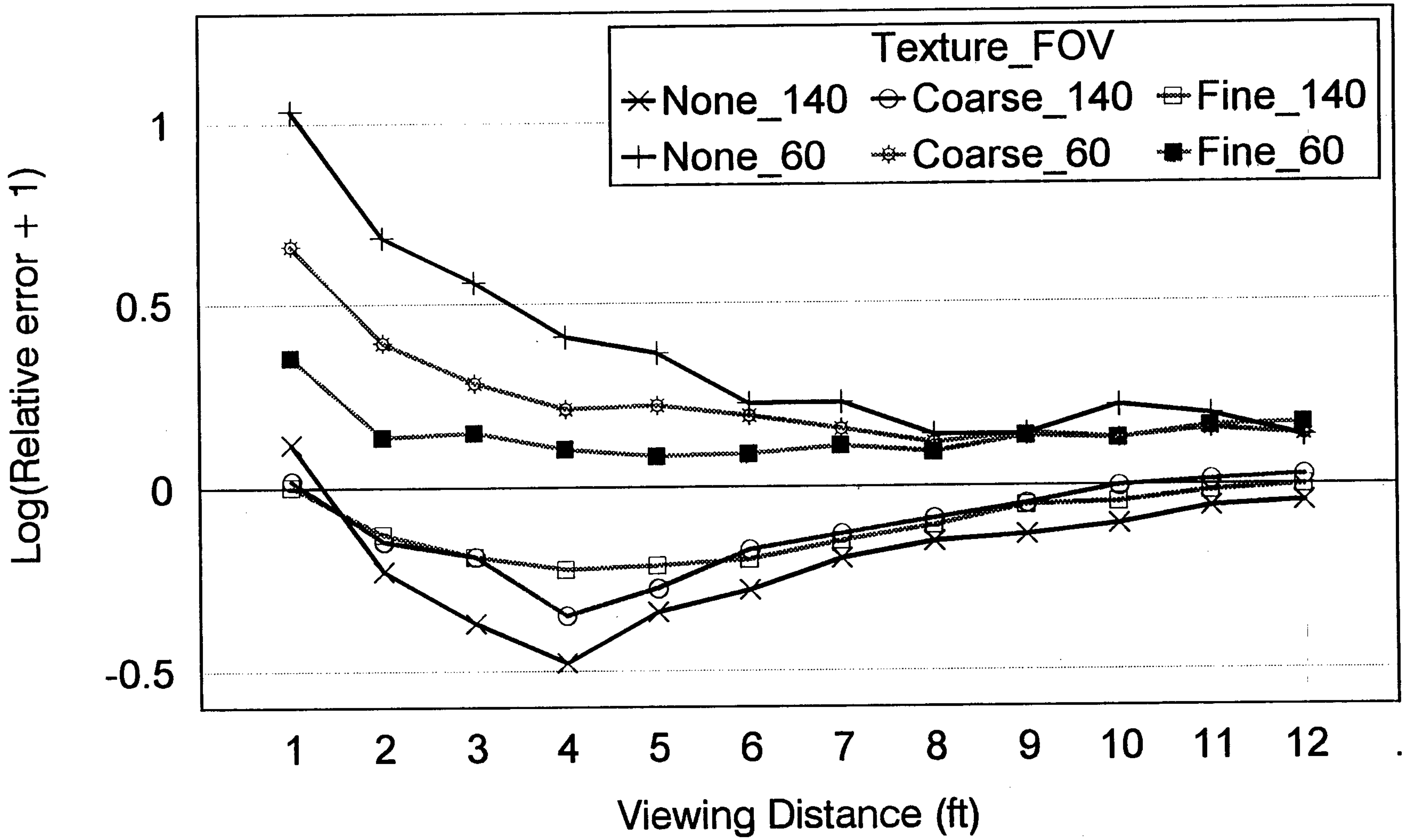

Figure 10. Relative error as a function of display FOV, wall texture, and viewing distance

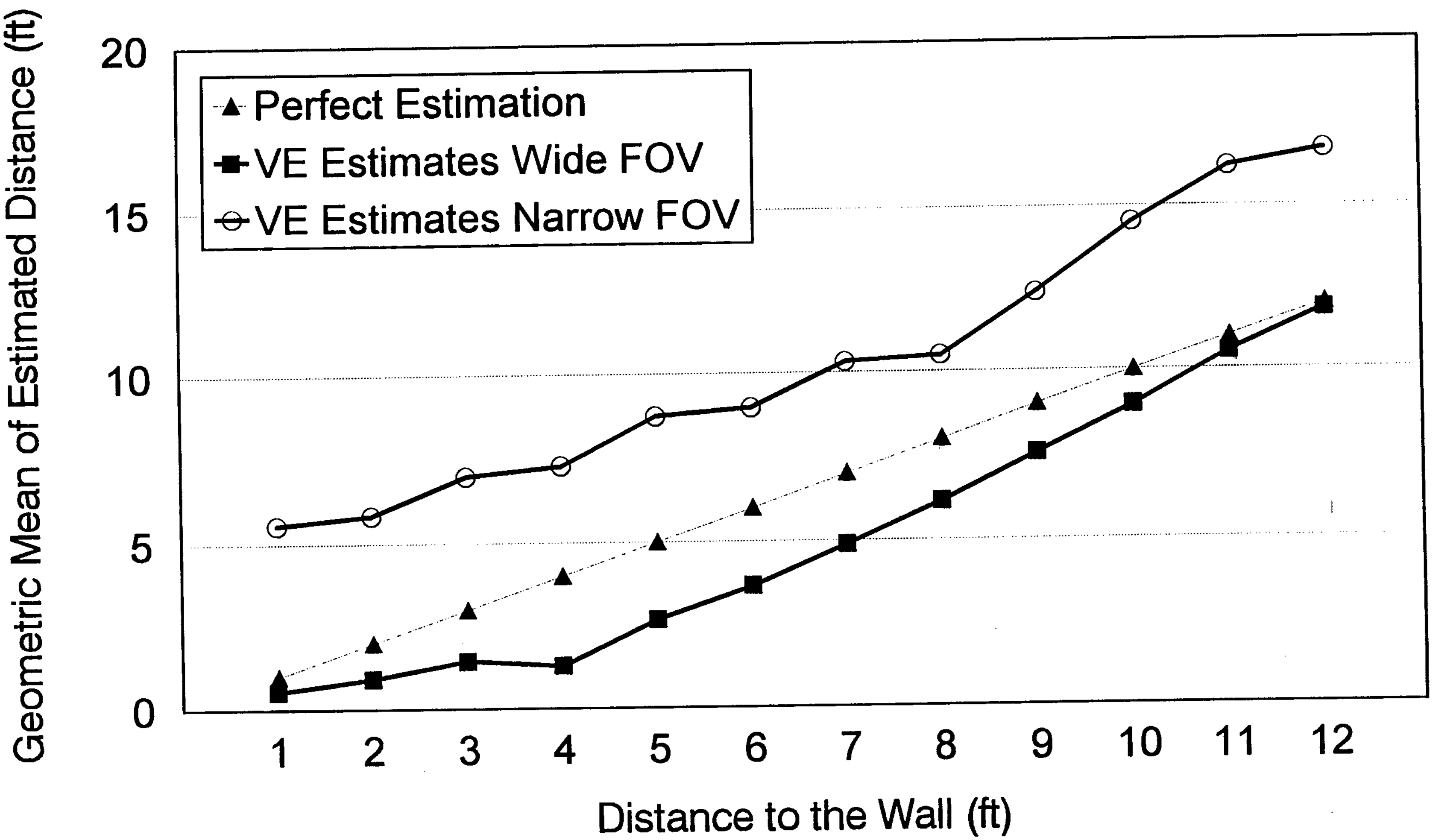

Figure 11. Geometric means of distance estimates as a function of display FOV viewing distance

General Discussion

The results of two experiments in which observers were required to estimate distances in a VE clearly support observations by Lampton et. al (1995) and by Wright (1995) that distance estimation in VE is poor relative to distance estimation in the real world. Results of our first experiment (distances from 10 to 110 feet) indicate that observers tend to underestimate distances both in VE and in the real world, but suggest that the tendency to underestimate is greater in VE. Manipulating the size of objects in the VE moderately influenced distance estimates, but changing the floor textures along the corridor influenced distance judgements very little. Our second experiment also suggests that observers tend to underestimate distances in VE at distances ranging from one to twelve feet. However when a narrow FOV reduces or eliminates linear perspective cues, observers overestimated the same distances that had been underestimated with a wide FOV. The absence of linear perspective increases the importance of other cues, such as textured wall patterns, which we found to clearly influence distance judgements at the closer distances. Two of the most frequently reported cues for judging distances with the narrow FOV were wall pattern size and wall pattern clarity. The addition of textured patterns yielded better distance discrimination and more accurate estimates. This kind of result is exactly what Wickens et al. (1989) had in mind when he suggested at close distances the elimination of linear perspective may enhance the importance of other cues.

Resolution, FOV, and Distance Estimation

In previous research Wright (1995) used a state-of-the-art Helmet Mounted Display with a very high resolution inset to investigate the ability of aviators to judge distance in a virtual environment, based on the mistaken assumption that the resolution of the display itself would be sufficient to overcome deficits in distance estimation in VE. Apparently he did not realize that other dominant cues for judging distance, such as linear perspective and various motion cues, would likely mask any beneficial effects of high resolution on the accuracy of estimates for the distances in question. In the present investigation, we examined the effects of the resolution of the wall pattern (referred to as texture) at distances of 12 feet or less, and determined that resolution interacts with distance and FOV to influence distance judgements. In our research, linear perspective was not available at the closer distances and motion cues were eliminated by restricting head and body movement. The elimination of these dominant cues enabled resolution to play a larger role in determining the accuracy of the estimates.

Many of the helmet-mounted displays (HMDs) currently on the market are sacrificing FOV in order to obtain higher resolution. Apparently manufacturers of these HMDs believe that resolution is more important for users of these helmets than is FOV. Based on our results, this trend to design high resolution, narrow FOV displays may have a deleterious effect on distance estimation and depth perception in VE. The stereoscopic view provided by some of these HMDs may not sufficiently compensate for the depth cues lost when using a narrow FOV. Additional compensatory cues may be needed with narrow FOV helmets, to include the liberal use of textured patterns, perhaps with emergent properties. Some training may be necessary to allow participants to make maximum use of compensatory cues. For example, if participants were instructed to observe how the size of the elements in an emergent pattern change with distance, this might allow them to improve the accuracy of their estimates.

Recommendations

The purpose of this research was to identify variables that influence the accuracy of distance estimates in VE and to determine if cues for distance in VE might be manipulated to compensate for the generally poor distance judgements in VE. Minimally this should lead to more accurate perceptions of depth and distance in VE, and perhaps also result in improved transfer to real world distance estimation. The following recommendations are offered based on our results. Researchers should consider our conclusions as preliminary, and should exercise caution in applying them prematurely for the following reasons: (1) Cues that were shown to be effective for a stationary observer with no motion cues may be less important when head and body movement are allowed; and (2) Cues that are essential for judging distance in VE may be less important in a real world environment where additional cues are available.

Reducing relative size of objects compared to their size in the real world may improve distance estimates in VE at the longer distances and reduce looming effects for the shorter distances. While reducing the size of objects in VE relative to their size in the real world may result in less underestimation in VE, it is not known how this reduction would affect subsequent real world estimates. In addition if all objects in VE were uniformly reduced in size, some objects at long distances in VE may not be detectable or, if detected, could not be recognized. Finally the objects used in this research were not objects of known size, so their ambiguity compared to more familiar objects may have enhanced their effects.

Choosing a wide FOV display can improve distance judgements, and should be used for tasks where these judgements are important. The addition of head movement, which was restricted in this research, may result in an increased availability of linear perspective cues for a given FOV, but it is not likely to fully compensate for a narrow FOV.

Texture and patterns on objects and walls may improve distance estimates at the closest distances where linear perspective is lost, and may be especially critical when using a narrow FOV display. The compensatory value of a pattern likely varies with the type of pattern and its resolution, so patterns or textures for walls or other objects should be carefully selected. Texture and pattern selection becomes even more important as FOV decreases.

This research provided only marginal support for the use of emergent patterns, but significant effects for pattern and pattern texture interactions suggest that this variable should not be ignored. This variable remains a viable candidate for improving the accuracy of distance estates in VE until further research suggests otherwise. Perceptual training may be the key to improving the usefulness of emerging patterns as a cue for distance.

Planned Research

We have just begun our evaluation of factors that may influence distance estimation in VE. Our next step is to add motion to evaluate how motion cues influence distance judgements. We believe that both the mode of locomotion and the perceived speed of locomotion can affect distance judgements. We also think that the number of visual changes along a traveled path can influence perceived distance. These variables as well as additional compensatory cues will be investigated in future experiments.

References

DeLucia, P. (1991). Pictorial and motion-based information for depth perception. Journal of Experimental Psychology: Human Perception and Performance, 17(3), 738-748.

DeMaio, J., Rinalducci,E.J., Brooks, R., & Brunderman, J. (1983). Visual cuing effectiveness: Comparison of perception and flying performance. Proceedings of the Human Factors Society 27th Annual Meeting, 928-932.

Gibson, J.J. (1979). The ecological approach to visual perception. Boston: Houghton Mifflin.

Galantner, E., & Galantner, P.(1970). Range estimates of distant visual stimuli. Perception and Psychophysics, 14(2), 301-306.

Garness, S.A, Flach, J.M. Stanard, T. (1994). The basis for the perception and control of altitude: Splay & depression angle components of optical flow. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting. 1275-1279.

Gibson, E.J., & Bergman, R. (1954). The effect of training on absolute estimation of distance over the ground. Journal of Experimental Psychology, 48, 473-482.

Hale, J.P., & Dittmar, M.L. (1994). Virtual reality as a human factors design tool for architectural spaces - control rooms to space stations I: Objective measures. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting. 275-279.

Howlett, E.M. (1990). Wide angle orthostereo. In J.O. Merritt and S.S. Fisher (Eds.) Stereoscopic Displays and Applications. Bellingham, WA: The International Society for Optical Engineering.

Jacobs,R.S., Crooks,W.H., Crooks,J.R., Colburn,E., Fraser, R.E, Gorman,P.F., Madden,J.L., Furness,T.A., & Tice,S.T. (1994). Training dismounted soldiers in virtual environments: Task and research requirements. (Technical Report 1011). Alexandria, VA: US Army Research Institute for the Behavioral and Social Sciences. (AD A286 311)

Jex, H.R. (1991). Some criteria for teleoperators and virtual environments from experiences with vehicle/operator simulation. In N.I. Durlach, T.B. Sheridan, and S.R. Ellis (Eds.) Human machine interfaces for teleoperators and virtual environments. Moffett Field, CA: NASA Conference Publication 10071.

Kaufman, L. (1974). Sight and mind. New York: Oxford University Press.

Kleiss, J.A. & Hubbard, D.C. (1993). Effects of three types of simulator visual scene detail on detection of altitude change. Human Factors, 35(4), 653-672.

Kolasinski, E.M. (1995). Simulator sickness in virtual environments. (ARI Technical Report 1027). Alexandria, VA: US Army Research Institute for the Behavioral and Social Sciences. (AD A295 861)

Lampton, D.R., Singer, M.J., McDonald, D., & Bliss, J.P. (1995). Distance estimation in virtual environments. Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting, 1268-1272.

Padmos, P. & Milders, M. (1992). Quality Criteria for Simulator Images: A Literature Review. Human Factors, 34(6), 727-7548.

Patterson, R., Moe, L., & Hewitt, T. (1992). Factors that affect depth perception in stereoscopic displays. Human Factors, 34(6), 655-668.

Pausch, R., Crea, T., & Conway, M. (1992). A literature survey for virtual environments: Military flight simulator visual systems and simulator sickness. Presence, 1(3), 344-363.

Psotka, J., Davison, S.A., Lewis, S.A., (1993). Exploring immersion in virtual space. Virtual Reality Systems, 1(2), 70-82.

Reardon, K.A., & Warren, R. (1989). Effect of emergent detail on descent estimations in flight simulators. Proceedings of the Fifth International Symposium on Aviation Psychology, 714-719.

Regan,E.C. (1993). Side-effects of immersion virtual reality. Paper presented at the International Applied Military Psychology Symposium., July 26-29.

Rinalducci, E.J. (1994). Characteristics of visual fidelity in the virtual environment. (ARI Technical Report). Alexandria, VA: US Army Research Institute for the Behavioral and Social Sciences.

Rinalducci, E.J., DeMaio, J., Patterson, M.J., & Brooks, R. (1983). Psychophysical assessment of simulator visual displays. Proceedings of the Ohio State Aviation Psychology Symposium.

Roscoe, S.N., (1984). Judgements of size and distance with imaging displays. Human Factors, 26(6), 617-629.

Rushton and Wann (1993). Problems in perception and action in virtual worlds. Proceedings of the Third Annual Conference on Virtual Reality. 43-55.

Surdick, R.T, Davis, E.T., King, R.A., Corso, G.M., Shapiro, A., Hodges, L., & Elliot, K. (1994). Relevant cues for the visual perception of depth: Is where you see it where it is? Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting. 1305-1309.

Stevens, S.S. (1986). Psychophysics. New Brunswick, NJ: Transaction Books. Original edition by John Wiley & Sons, Inc.

Weinstein, L.F. (1989). Ground-texture information for aimpoint estimation. Proceedings of the Fifth International Symposium on Aviation Psychology, 737-742.

Wickens, C.D. (1990). Three-dimensional stereoscopic display implementation: Guidelines derived from human visual capabilities. SPIE proceedings vol. 1256, Santa Clara, CA.

Wickens,C.D., Todd,S., and Seidler,K., (1989) Three-dimensional displays: Perception, implementation, and applications, "CSERIAC SOAR 89-001 Technical report, AFAAMRL, Wright-Patterson AFB, Ohio, 1989.

Witmer, B.G., Bailey, J.H., Knerr, B.W. (1994). Training dismounted soldiers in virtual environments: Route learning and transfer. (ARI Technical Report 1022). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences. (AD A 292 900)

Witmer, B.G. & Singer, M. (1994). Measuring presence in virtual environments. (ARI Technical Report 1014). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences. (AD A286 183)

Wright, R.H. (1995). Virtual reality psychophysics: Forward and lateral distance, height and speed perceptions with a wide angle helmet display. (ARI Technical Report 1025). Alexandria, VA: US Army Research Institute for the Behavioral and Social Sciences. (AD A294 027)

Appendix A. Proximate Task Post-experiment Questionnaire

Exp 4.1A Post Questionnaire

S# ________ Date __________

Complete the questions listed below in the order that they appear. Do not return to a previous question to change your response or to include additional informaton.

1. Overall, how would you rate you ability to accurately judge distance? (Circle a number)

Poor	Below average	Average	Above average	Excellent
1	2	3	4	5

For the distance estimation tasks performed in the virtual environment,

2. Please list the primary distance cue(s) which you used in making your estimates? Please explain how you used each cue.

Cue?	How used?
____________________	________________________________
____________________	________________________________
____________________	________________________________

3. Which of the following personal attributes **was most helpful to you** in making accurate judgements of distance. (Check one)

____ Good spatial abilities
____ Good depth perception
____ Good quantitative skills
____ Good visual memory
____ An accurate internal metric for units of distance

4. Which of the following personal attributes do you think **could be most helpful** in improving your accuracy in judging distance (i.e., if you were better at this skill/ability). (Check one)

____ Better spatial abilities
____ Better depth perception
____ Better quantitative skills
____ Better visual memory
____ More accurate internal metric for units of distance

During the experiment, how much did you use each of the following cues in making your judgements of distance (Circle a number for each).

5. Perceived size of object.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

6. Floor pattern.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

7. Perceived width of the corridor.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

8. Intersection between the object and the floor.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

9. Wall pattern.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

10. Perceived height of the corridor.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

11. Other cue not listed here (e.g., one from question 2 above.

Cue: ____

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

12. Please rank **how important each of the following cues was** in making your distance estimates during the experiment. Place a 7 by the most important cue, a 6 by the next most important cue, and so on until all cues have been ranked.

Rank	**Cue**
________	Perceived object size
________	Floor pattern
________	Perceived width of the corridor
________	Intersection between the object and the floor
________	Wall pattern.
________	Perceived height of the corridor
________	Other cue listed in question 11

Appendix B. Proximate Task Post-experiment Questionnaire

Exp 4.1B Post Questionnaire

S# ________ Date __________

Complete the questions listed below in the order that they appear. Do not return to a previous question to change your response or to include additional informaton.

1. Overall, how would you rate you ability to accurately judge distance? (Circle a number)

Poor	Below average	Average	Above average	Excellent
1	2	3	4	5

For the distance estimation tasks performed in the virtual environment,

2. Please list the primary distance cue(s) which you used in making your estimates? Please explain how you used each cue.

Cue?	How used?
________________________	____
________________________	____
________________________	____

3. Which of the following personal attributes **was most helpful to you** in making accurate judgements of distance. (Check one)

____ Good spatial abilities
____ Good depth perception
____ Good quantitative skills
____ Good visual memory
____ An accurate internal metric for units of distance

4. Which of the following personal attributes do you think **could be most helpful** in improving your accuracy in judging distance (i.e., if you were better at this skill/ability). (Check one)

____ Better spatial abilities
____ Better depth perception
____ Better quantitative skills
____ Better visual memory
____ More accurate internal metric for units of distance

During the experiment, how much did you use each of the following cues in making your judgements of distance (Circle a number for each).

5. Perceived size of wall.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

6. Perceived width of the corridor.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

7. Intersection between the wall and the floor.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

8. Perceived size of wall pattern.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

9. Perceived clarity of wall pattern.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

10. Perceived height of the corridor.

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

11. Other cue not listed here (e.g., one from question 2 above.

Cue: ______________________________

Never	Sometimes	Neither	Frequently	Always
1	2	3	4	5

12. Please rank **how important each of the following cues was** in making your distance estimates during the experiment. Place a 7 by the most important cue, a 6 by the next most important cue, and so on until all cues have been ranked.

Rank	**Cue**
________	Perceived wall size
________	Perceived width of the corridor
________	Intersection between the wall and the floor
________	Perceived size of wall pattern.
________	Perceived clarity of wall pattern.
________	Perceived height of the corridor
________	Other cue listed in question 11